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# OPTICAL ALIGNMENT (ADVANCED)

## TRAINING MANUAL

(NASA-TM-72504) OPTICAL ALIGNMENT  
(ADVANCED) TRAINING MANUAL (NASA) 155 P

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# NASA TECH BRIEF

## Marshall Space Flight Center



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### Measurement of Dimensions and Alignment with Optical Instruments

For several centuries, navigators, surveyors, and builders have used optical instruments as measuring devices. Today, industry is applying similar techniques in measuring alignment and dimensions of finished products. Indeed, it is not uncommon to encounter products that meet the dimensional requirements of one part in 200,000 regardless of size. To meet such requirements, optical inspection tools are used instead of micrometers, calipers, surface plates, and gauges, particularly in measurements of large components and systems. This technique, called optical tooling, is already in use in the aerospace industry.

To meet increased demands for personnel training in optical tooling, an advanced manual entitled *Optical Alignment* has been published for use as a handbook in conjunction with an advanced optical alignment training course. The course, as contained in this manual, encompasses the principles involved in determining and applying the proper optical tooling devices to fulfill the precise measuring requirements. The information covered by the manual incorporates such subjects as versatility of optical alignment, interpretation of design specifications in relation to optical tooling selections, and tooling limitations. Topics include the following:

1. discussion of design tolerances and references,
2. calibration and test of optical tooling instruments,
3. planning of optical alignment,

4. alignment of jaws which hold down rocket booster during static firing,
5. determination of the geometric thrust vector rocket engine alignment by establishing the centroid of the throat and exit areas.
6. alignment of rocket power units,
7. determination of flatness of canted planes, and
8. establishing a true north line by observation of Polaris.

#### Notes:

1. Information concerning the advanced optical alignment training manual may be of interest to personnel engaged in optical alignment methods such as surveyors, builders, quality control engineers, and test engineers.
2. A more basic training manual on optical alignment is described in Tech Brief 68-10574.
3. Requests for further information may be directed to:  
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# **RELIABILITY AND QUALITY ASSURANCE TRAINING PROGRAM**

## FOREWORD

This manual was prepared for the purpose of presenting information to personnel of the National Aeronautics and Space Administration, other government agencies, and contractor personnel who attend the advanced optical alignment course.

Skilled technicians with many years experience serve as instructors in the techniques required for qualification in this specialized training.

Certification of individuals will be determined by the instructors. Training will be accomplished under the guidance of Quality and Reliability Assurance Laboratory personnel at the George C. Marshall Space Flight Center, Huntsville, Alabama.

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## SECTION I. INTRODUCTION

In most manufacturing processes, it is imperative that size and alignment must be measured and controlled to maintain quality of the end product.

With the advent of the increase in product size, aerospace and industrial requirements demanded more sophisticated inspection tools than were available. Dimensions and tolerances were beyond the limits of contemporary inspection tools, such as, micrometers, calipers, surface plates, gauges, etc. Thus, optical tooling was adopted as a solution for determining the physical characteristics within the desired tolerances of space vehicles and component parts.

Optical tooling methods have been used for many years by surveyors and builders. These basic methods have been improved through redesign of the existing optical instruments. Subsequently, the field of measuring large objects has been expanded to almost unlimited boundaries. The degree of accuracy of one part in 200,000 is the accepted standard, regardless of size.

As the degree of accuracy any tool will render depends upon how well it is applied, the Advanced Optical Alignment course, as contained in this volume, encompasses the principles involved in determining and applying the proper optical tooling devices to fulfill the measuring requirements. Course content incorporates such subjects as versatility of optical alignment, interpretation of design specifications in relation to optical tooling selections, and tooling limitations.

When considering the employment of optical tools, the accuracy of an alignment measurement is directly affected by instrument quality, skill of the equipment operator, and complexity of tooling setup. Alignment can be accomplished many times by a combination of optical as well as mechanical devices. Whenever practical and also to save time and money, a simple mechanical device will accomplish the same result as an elaborate tooling setup. Utilization of excessive equipment merely introduces error.

## SECTION II. TOLERANCES AND REFERENCES

### A. Introduction

Engineering drawings are the primary source of information in any manufacturing process. An engineering drawing is a picture of an object that contains sufficient information for the manufacture of that object. The drawing establishes the limits of size and shape through the use of dimensions and tolerances. Dimensions on a drawing give the distance from one feature or datum plane to another feature. The datum lines and planes that are used to control all characteristics of an assembly are known as basic references.

To apply optical tooling to a problem of alignment or measurement, certain conditions must exist. The exact drawing requirements must be known. The basic reference system of the workpiece must be established. The instrumentation must be set up with a known relationship to the reference. The purpose of this section is to introduce general rules of tolerance and basic references and illustrate a method of bringing an object under optical control. The section on tolerancing is in accordance with the NASA Drafting Manual and MIL-STD-8-B.

### B. Definitions

**Allowance** - An allowance is a prescribed difference between the maximum material condition of mating parts. It is the minimum clearance (positive allowance) or maximum interference (negative allowance) between such parts.

**Clearance** - Clearance is the total space between the mating parts.

**Concentricity** - Concentricity is a condition in which two or more regular features (such as cylinders, cones, spheres, hexagons, etc.) in any combination have a common axis.

**Datum Elements** - Datum parts, lines, and surfaces are features assumed to be exact for purposes of computation or reference and from which the location of other features may be established.

**Dimension** - A dimension is a numerical value expressed in appropriate units of measure and indicated on drawings with lines, symbols, and notes to define the geometrical characteristics of an object.

**Basic Dimension** - A dimension specified on the drawing as basic is a theoretical value used to describe exact size, shape, or location of a feature. It is used as a basis from which permissible variations are established by tolerances on other dimensions or notes.

**Form Dimension** - A form dimension is one which specifies a feature of an object which cannot be properly defined by dimensions of size or location. Examples of form dimensions are the angle of the frustrum of a cone, the involute of a gear tooth, and the angle of a thread.

**Location Dimension** - A location dimension is one which specifies the position or distance relationship of one feature of an object with respect to another.

**Reference Dimension** - A reference dimension is a dimension without tolerance used for informational purposes and does not govern manufacturing and inspection operations in any way.

**Size Dimension** - A size dimension is a specified value of a diameter, width, length, or other geometrical characteristic directly related to the size of an object.

**Angular Dimensioning** - The angular dimensioning system is a method for indicating the position of a point, line, or surface by means of linear dimensions and angle, other than the  $90^\circ$  angle implied by the horizontal and vertical centerlines.

**Rectangular Dimensioning** - The rectangular dimensioning system is a method for indicating distances, locations, and sizes by means of linear dimensions measured parallel to reference lines or planes which are perpendicular to each other.

**Eccentricity** - Eccentricity is a condition where the axis of a particular feature is parallel to, but offset from, the axis of another feature; or where the axis of a rotating part mounted in an assembly does not coincide with the axis of the part about which it turns.

**Feature** - Features are specific characteristics or component portions of a part which may include one or more surfaces such as holes, screw threads, profiles, or rabbets.

**Fit** - Fit is the general term used to signify the range of tightness which may result from the application of a specific combination of allowances and tolerances in the design of mating parts.

**Actual Fit** - The actual fit between two mating parts is the relation existing between them with respect to the amount of clearance or interference which is present when they are assembled.

**Clearance Fit** - A clearance fit is one having limits of size so prescribed that clearance always results when mating parts are assembled.

**Interference Fit** - An interference fit is one having limits of size so prescribed that an interference always results when mating parts are assembled.

**Transition Fit** - A transition fit is one having limits of size so prescribed that either a clearance or an interference may result when parts are assembled.

**Interchangeability** - A condition of design wherein any and all mating parts will assemble and function properly without the need for any machining or fitting at assembly.

**Interference** - Interference is the total amount of deformation which must be effected in order to force an internal member into a smaller external member.

**Limits** - The limits are the maximum and minimum values prescribed for a specific dimension. The limits may be of size if the dimension concerned is a size dimension or they may be of location if the dimension concerned is a location dimension.

**Maximum Material Condition (MMC)** - Maximum material condition is that condition wherein the part contains the maximum amount of material. For example, the maximum material condition of a shaft occurs at its high limit of size and that of a hole at its low limit of size.

**Minimum Material Limit** - A minimum material limit is the minimum limit of size of an external dimension or the maximum limit of size of an internal dimension.

**Size** - Size is a designation of magnitude. When a value is assigned to a dimension it is referred to hereinafter as the size of that dimension.

#### NOTE

It is recognized that the terms "dimension" and "size" are both used at times to convey the meaning of magnitude.

**Actual Size** - An actual size is a measured size.

**Basic Size** - The basic size is that size from which the limits of size are derived by the application of allowances and tolerances.

**Design Size** - The design size is that size from which the limits of size are derived by the application of tolerances. When there is no allowance the design size is the same as the basic size.

**Nominal Size** - The nominal size is the designation which is used for the purpose of general identification. For example, a rod may be referred to as 1/4 inch, though the actual dimension on the drawing is 0.2495 inch. In this case 1/4 inch is the nominal size.

**Limits of Size** - The limits of size are the applicable maximum and minimum sizes.

**Tolerance** - A tolerance is the total permissible variation of size, form, or location.

**Unilateral Tolerance** - A unilateral tolerance is a tolerance in which variation is permitted only in one direction from the design size.

**Bilateral Tolerance** - A bilateral tolerance is a tolerance in which variation is permitted in both directions from the design size.

**Typical** - The term "typical", when associated with a dimension means that this dimension applies to all features that appear to be identical in size and configuration. The tolerance stated for a dimension labeled typical also applies to each apparently identical feature.

### C. General Tolerance Notes

When the same tolerance applies to several dimensions on a drawing, repetition of the most common tolerance applicable to decimals, fractions, and/or angles should be avoided by entering such general tolerances in the supplementary block, under the heading "Unless Otherwise Specified." Such general tolerance notes apply to each dimension on a drawing except for the following:

- (1) Dimensions having tolerances assigned directly.
- (2) Dimensions labeled "REF," "MAX," "MIN," or "BASIC."
- (3) Dimensions covered by a general tolerancing note relating to a specific category of dimensions.

Examples:

- (a) CASTING TOLERANCE .006/IN. OR .030, WHICHEVER IS GREATER.
- (b) DIMENSIONS LOCATING THE TRUE POSITION ARE BASIC.
- (4) Dimensions which have tolerance controlled by documents invoked by the drawing.

### D. Symbols

When symbols are used in lieu of, or in conjunction with notes to express positional or form tolerances, they shall be the symbols shown herein.

#### 1. Geometric Characteristic Symbol

The symbols shown in Figure 2-1 shall be used to state the geometric characteristics being toleranced.













	FLATNESS & STRAIGHTNESS		ROUNDNESS
	ANGULARITY		SYMMETRY
	PERPENDICULARITY		(MMC) MAXIMUM MATERIAL CONDITION
	PARALLELISM		(RFS) REGARDLESS OF FEATURE SIZE
	CONCENTRICITY		
	TRUE POSITION		

Figure 2-1. Geometric Characteristic Symbols

## 2. Feature Control Symbol

When symbols are used, a positional or form tolerance shall be stated by means of the feature control symbol illustrated by Figure 2-2. The geometric characteristic symbol shall be followed by the permissible tolerance, and in some cases by the modifier  or . The height of the box outline of the symbol shall be 1/4 inch, and the length shall be 1 1/4 inches. When characters in addition to the characteristic symbol, datum reference, and tolerance must be specified, the length of the box should be increased as necessary to avoid crowding. The feature control symbols shall be associated with the feature(s) being tolerated by one of the following methods.

- (1) Adding the symbol to a note pertaining to the feature(s).
- (2) Running a leader line from the symbol to the feature.
- (3) Attaching a side, end, or corner of the box to an extension line from the feature.
- (4) Attaching a side or end of the box to the dimension line pertaining to the feature when it is cylindrical.



Figure 2-2. Feature Control Symbol

### 3. Datum Identifying Symbol

Each datum (excepting implied datums) on a drawing shall be assigned a different identifying reference letter, for which any letter of the alphabet, except "I", "O", and "Q" may be used. The datum identifying symbol shall be formed by a rectangle containing the datum reference letter preceded and followed by a dash (Figure 2-3). The datum identifying symbol shall be associated with the surface being designated as a datum. Each datum identifying symbol shall be used only once on a drawing (Figure 2-3).

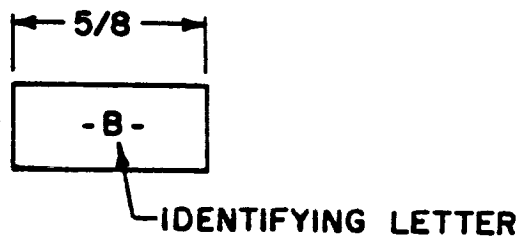


Figure 2-3. Datum Identifying Symbol

### 4. Reference to Datum

When a positional or form tolerance must be related to a datum, this relationship shall be stated by placing the datum reference letter between the geometric characteristic symbol and the tolerance. If there are two or more datums, or if the modifiers (M) or (S) are used, vertical lines shall be added to provide clarity (Figure 2-4).

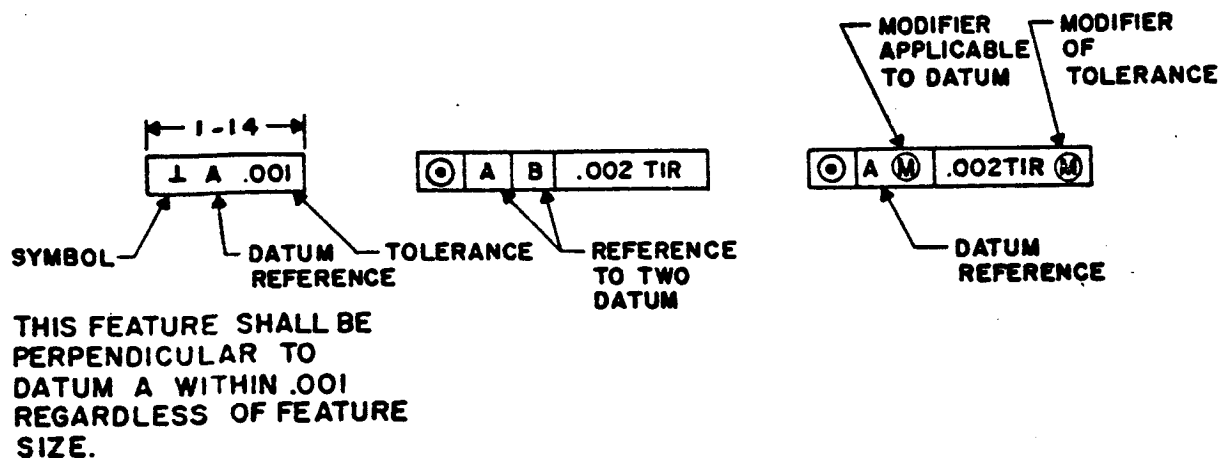


Figure 2-4. Feature Control Symbol  
Incorporating Datum Reference

#### 5. Combined Symbols

When a feature serves as a datum and also is controlled by a positional or form tolerance, the feature control symbol and the datum identifying symbol shall be combined as shown in Figure 2-5. In such cases, the length of the box for the datum identifying symbol may be either the same as that of the feature control symbol or 5/8 inch.



Figure 2-5. Combined Feature Control Symbol  
and Datum Identifying Symbol

## 6. General

Figure 2-6, A through C illustrate the location of holes or other features by means of rectangular coordinates or angular dimensioning. In the past, these coordinates and angular dimensions predominantly have been shown with individual tolerances. This results in a square, rectangular, or wedge-shaped tolerance zone, as shown by Figure 2-6, A and C. The engineering intent can often be expressed more precisely if locations are given as true positions, with tolerances to state how far actual positions can be displaced from true position. This results in a circular tolerance zone (Figure 2-6, C).

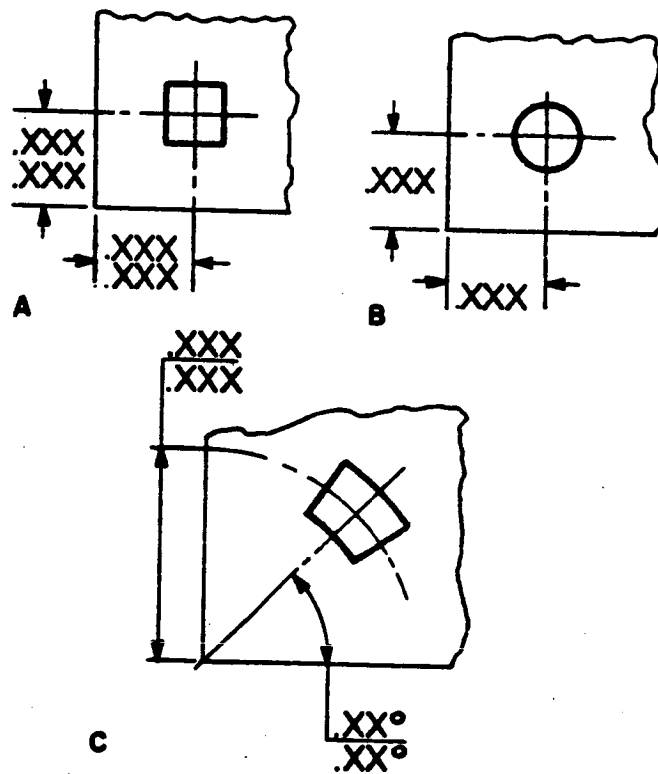


Figure 2-6. Tolerance Zone Interpretation

## 7. True Position

True position denotes the basic or theoretically exact position for a feature. The geometry involved in establishing the true position is perfect. All lines drawn perpendicular to one another and involved in establishing the true position of a pattern shall be interpreted to be at an angle of 90 (+0) degrees (90 basic), even though no angle is specified. All dimensions (rectangular, linear, or angular) that locate the true position with reference to either datums, or other features in the same pattern, shall be interpreted as perfect (true).

## 8. True Position Tolerance

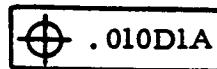
A true position tolerance is the total permissible variation in the location of a feature about its true position. For cylindrical features (holes and bosses) the true position tolerance is the diameter of the tolerance zone within which the axis of the feature must lie, the center of the tolerance zone being at the true position. For other features (slots and tabs) the true position tolerance is the total width of the tolerance zone within which the center plane of the feature must lie, the center plane of the zone being at the true position. Specifying true position tolerances, the following methods apply:

Specify the true position of each feature in a pattern (groups of holes, slots, tabs, etc) by untoleranced dimensions in any suitable form.

When features are located by dimensions to their axes and when the location may be allowed to vary in any direction, the zone of tolerance, which in this case is a cylinder, shall be specified by either of the following typical methods:

(1) 6 HOLES .XXX DIA LOCATED AT TRUE POSITION  
WITHIN .010 DIA.

(2) 6 HOLES .XXX DIA



## 9. Significance of "MMC" and "RFS"

MAXIMUM MATERIAL CONDITION and REGARDLESS OF FEATURE SIZE are used as modifiers of positional and form tolerances and datum references. The modifiers may be abbreviated

"MMC" or "RFS". The use of the symbols  $\textcircled{M}$  or  $\textcircled{S}$  is restricted to the feature control symbol.

The maximum material condition of a part is that condition wherein the part contains the maximum amount of material, e. g., minimum hole size and maximum shaft size.

The application of MMC to a positional or form tolerance means that the tolerance applies at MMC and is increased as the feature(s) depart(s) from MMC by the amount of such departure.

The application of RFS to a positional or form tolerance means that this tolerance must be adhered to regardless of the actual size to which the feature(s) is produced.

#### 10. General Rules

Rule 1. TRUE POSITION TOLERANCES APPLY AT MAXIMUM MATERIAL CONDITION, UNLESS OTHERWISE SPECIFIED. MMC applies both to the toleranced features and to any datum reference.

Rule 2. ALL OTHER POSITIONAL OR FORM TOLERANCES APPLY REGARDLESS OF FEATURE SIZE, UNLESS OTHERWISE SPECIFIED. RFS applies both to the toleranced features and to any datum reference.

Exceptions to the general rules shall be expressed in one of the following ways:

- (1) By the use of  $\textcircled{S}$  or  $\textcircled{M}$  in symbols.
- (2) By the addition of "REGARDLESS OF FEATURE SIZE" (or "RFS") or "MAXIMUM MATERIAL CONDITION" (or "MMC"), as appropriate, in each applicable drawing note.

- (3) By the use of a general note. If no modifiers are shown on a drawing, but this standard is referenced, the general rules stated above apply.

Optionally, the proper modifier may be expressed in connection with each positional or form tolerance and each reference, with the following exceptions:

- (1) Flatness, perpendicularity, or angularity of plane surfaces.
- (2) Datums that are planes.

Rule 3. ALL TOLERANCES specified in connection with true position and form tolerancing shall be TOTALS. Such terms as DIA, TIR, TOTAL, or WIDE ZONE emphasize that the tolerance is total.

## E. True Position Tolerancing

### 1. Interrelated Geometric Characteristics

In some cases it may be necessary to control the geometrical accuracy of a feature by means of different tolerances of form which are:

- (1) Both (or all) governed by a single tolerance value.
- (2) Each related to a different datum.
- (3) Intended for a simultaneous check of both (or all) geometric requirements.

The two (or more) geometric characteristics with their respective datums and the single tolerance shall be shown in the same figure control symbol as illustrated in Figure 2-7.

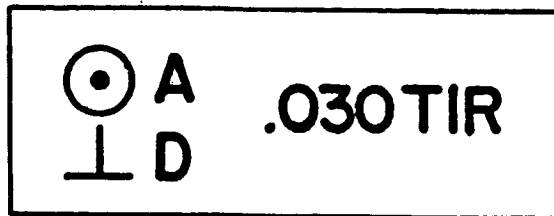


Figure 2-7. Interrelated Geometric Characteristics

When features are located by dimensions to a center plane or to one surface of the feature, positional tolerancing shall be applied by the use of either of the following methods.

When a part and its mating part have matching feature patterns, and alignment between such parts depends upon a functional feature such as a pilot, bore, or surface, this feature should be used as a datum. In such cases, the relationship between the true position tolerance and the datum shall be specified by either of the following typical methods:

- (1) 6 HOLES .XXX DIA, LOCATED AT TRUE POSITION WITHIN .010 DIA IN RELATION TO DATUM A.

- (2) 6 HOLES .XXX DIA  .010DLA

2. Identifying Dimensions Establishing the True Position

When true position tolerancing is used on a drawing, the untoleranced dimensions locating the true positions shall be identified by one of the following methods:

- (1) Add the word BASIC or the abbreviation (BSC) to the right of, or underneath, each dimension establishing the true position.
- (2) Tolerance each dimension on the drawing not involved in true position dimensioning, or

not labeled "REF", "MAX", or "MIN", and add the following note: "DIMENSIONS LOCATING THE TRUE POSITION ARE BASIC."

### 3. True Position Interpretation

In terms of the axis of the hole, the true position tolerance means that when RFS is the modifier, or when MMC is the modifier and the hole is at its maximum material condition, the axis of the hole must lie within a cylindrical zone having a diameter equal to the true position tolerance and having its center at the true position. The tolerance zone is perpendicular to the surface on which the holes originate and to which they have been illustrated on the drawing as being perpendicular; hence, the tolerance zone also defines the limits of variation in perpendicularity of each hole with respect to such surface, which is an implied datum surface. For a pattern of holes the cylindrical tolerance zones are parallel so that the true position tolerance controls both position and parallelism. When no modifier or MMC is specified it is only when the feature is at MMC that the true position tolerance applies. When the feature is at other than its maximum material condition (but within its limits of size) an additional tolerance is permitted. Such added tolerance is equal to the difference between MMC and the actual size of the feature.

### 4. Implied Datum Surfaces

Figure 2-8 shows four ways of expressing the true position relationship of a two-hole pattern to three datum surfaces. In views (A-1) and (A-2) the left-hand edge and lower edge of the plate are datums, because the basic dimensions locating the holes are measured from those surfaces. The top surface of the plate is an implied datum surface, as explained in paragraph above. In views (A-3) and (A-4) the three datum surfaces not only are specified, but the accuracy of these surfaces and their relationship to one another is controlled by geometric tolerances. This is in accord with the requirement that datum surfaces must be more accurate than locations established therefrom. Essentially, there is little difference between the requirements of views (A-1), (A-2), (A-3), or (A-4) with the exception that slightly greater inaccuracies of datum surfaces would be permissible under (A-1) and (A-2) in comparison with (A-3) and (A-4). Nevertheless even

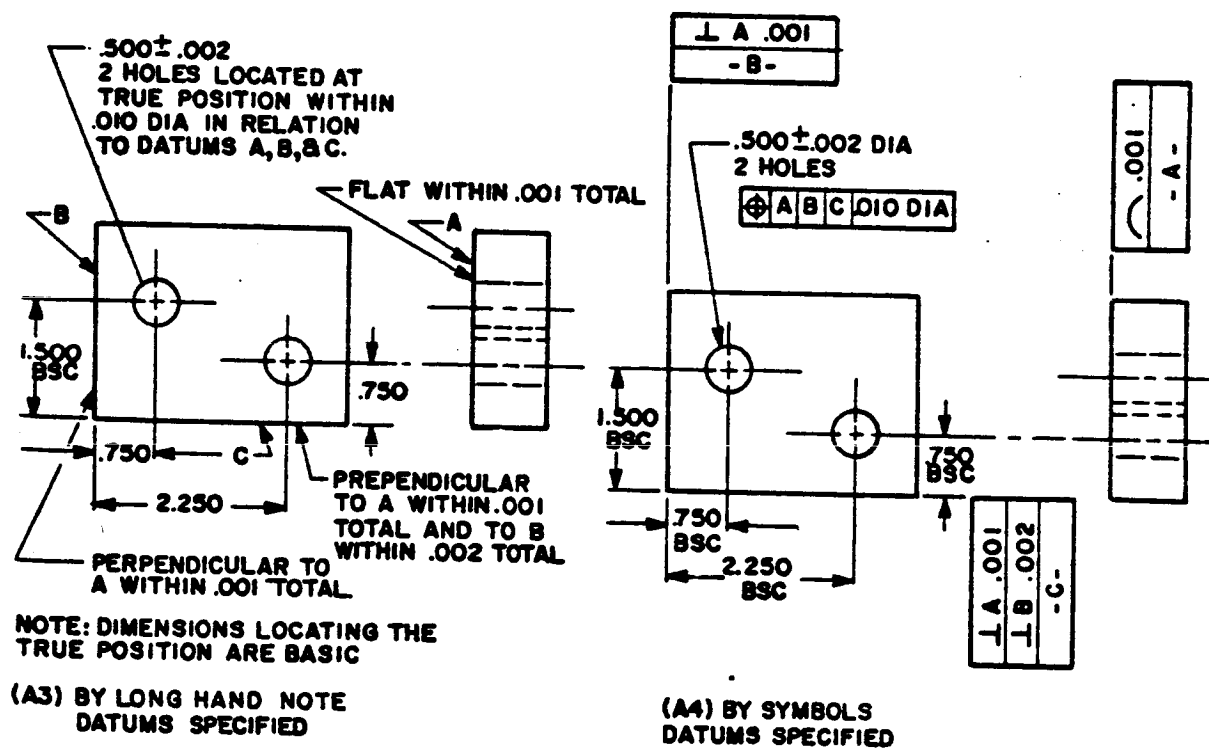
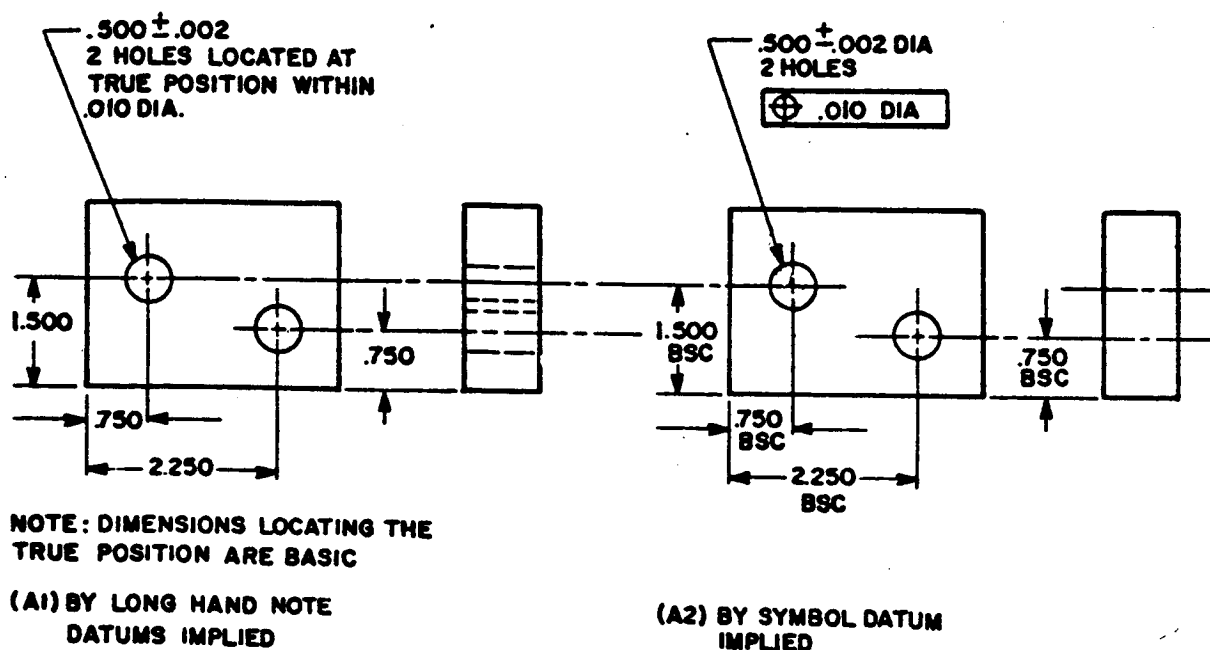


Figure 2-8. True Position

the case of views (A-1) and (A-2), the perpendicularity of the three datum surfaces to one another must be held within close limits or the part will not be accepted under normal gage practices.

## **F. Basic References**

Basic references are lines or planes from which all features of an object are positioned. The geometric relationship of these lines and planes is perfect, they are established without tolerance. These may include but are not limited to the following:

- (1) Centerlines
- (2) Waterlines or planes
- (3) Buttic lines or planes
- (4) Station lines or planes
- (5) Pitch plane
- (6) Yaw plane
- (7) Fin lines or planes.

In designing a system such as an airplane or space vehicle, the basic references are established for the entire system. Each assembly or stage is built from these references as are subassemblies. Since every assembly is built from the same reference system, a study of the tolerances will give the limits of size and configuration. The tolerance allowed will depend upon the design requirements for the structure, methods of manufacture, and assembly clearance requirements.

Tooling, for fabrication and assembly of parts, should be designed and built from the basic reference system of the assembly. Thus tolerance can be applied to dimensions that control locators, which position parts, in such a way as to be compatible with the design requirements for the assembly. When tooling is designed to be built with the aid of optical instruments, lines of sight can be used as the basic references and direct measurements to the locators are possible.

In either case the tooling should provide a method of indexing the assembly in relation to the basic references. Then when the assembly is removed from the tool these index marks are used as alignment references. Index marks may be optical targets, tooling holes, scribed lines, or machined surfaces that are used to establish a datum.

Generally, stages that are fabricated and assembled in the horizontal position have centerlines defined as passing through the centers of each end ring. Index marks are transferred from the assembly fixture to the ring during fabrication. Points A, B, C, and D, Figure 2-9, represent index marks for locating the fin planes for the forward end of the stage. A line passing through points B and C might not be perpendicular to a line through points D and B because these points are physical objects, and as such have a manufacturing tolerance applied to their location. However, the reference planes established by these points do not have a tolerance, their relationship is perfect.

In Figure 2-9 a line passing through points B and D establishes the forward end of a reference plane. The other reference plane is perpendicular to line BD, at point P'. P' is the intersection of lines BD and AC and is the center of the forward end ring. Points J, K, L, and M are index marks used to position the aft end ring. The location of these points has a tolerance and the relationship between the forward and aft rings also has a tolerance. Thus it is necessary to use one set of points as a rotational index. To establish the other reference planes, the difference between the basic rotational references and all other references must be split out.

In Figure 2-9 the centerline of the stage is a line passing through points P and P'. P' is the intersection of lines BD and AC, P is the intersection of lines JL and KM. Points B and D are the rotational index. They also establish the II - IV fin plane and the yaw plane. Fin plane I - III, or the pitch plane is perpendicular to II-IV or the yaw plane, and intersects it at the stage center line.

In order to assemble a stage in the horizontal position the stage centerline must be horizontal and the pitch plane or yaw plane vertical. When this is accomplished gravity seeking devices can be



used to determine the geometric relationship of all components to the basic references and consequently to each other. To level the centerline of the stage, Figure 2-9 points B and D are brought to the same elevation. P is then brought to this elevation by bringing M as far above DB as K is below DB.

When stages are designed to be assembled in the vertical position (Figure 2-10), the centerline is generally defined as being perpendicular to the aft surface of the aft ring. The pitch plane is also perpendicular to this surface and contains the stage centerline. The yaw plane is perpendicular to the pitch plane and intersects it at the stage centerline. To make the stage centerline vertical it is only necessary to level the aft ring surface.

Boosters of large diameters can be setup within extremely close angular tolerance by leveling the aft ring. Since this is the firing position of the booster, alignment data is directly related to the stage references. With smaller diameters it is more accurate to work with the length rather than the diameter. However, data taken in the horizontal position will be affected by deflection, due to the weight of the booster. For this reason, in horizontal alignment, it is necessary to provide a means of rotating the booster. All data must be taken with the booster in two positions, 180 degrees apart. The true position of any component will be the mean of its measured locations.

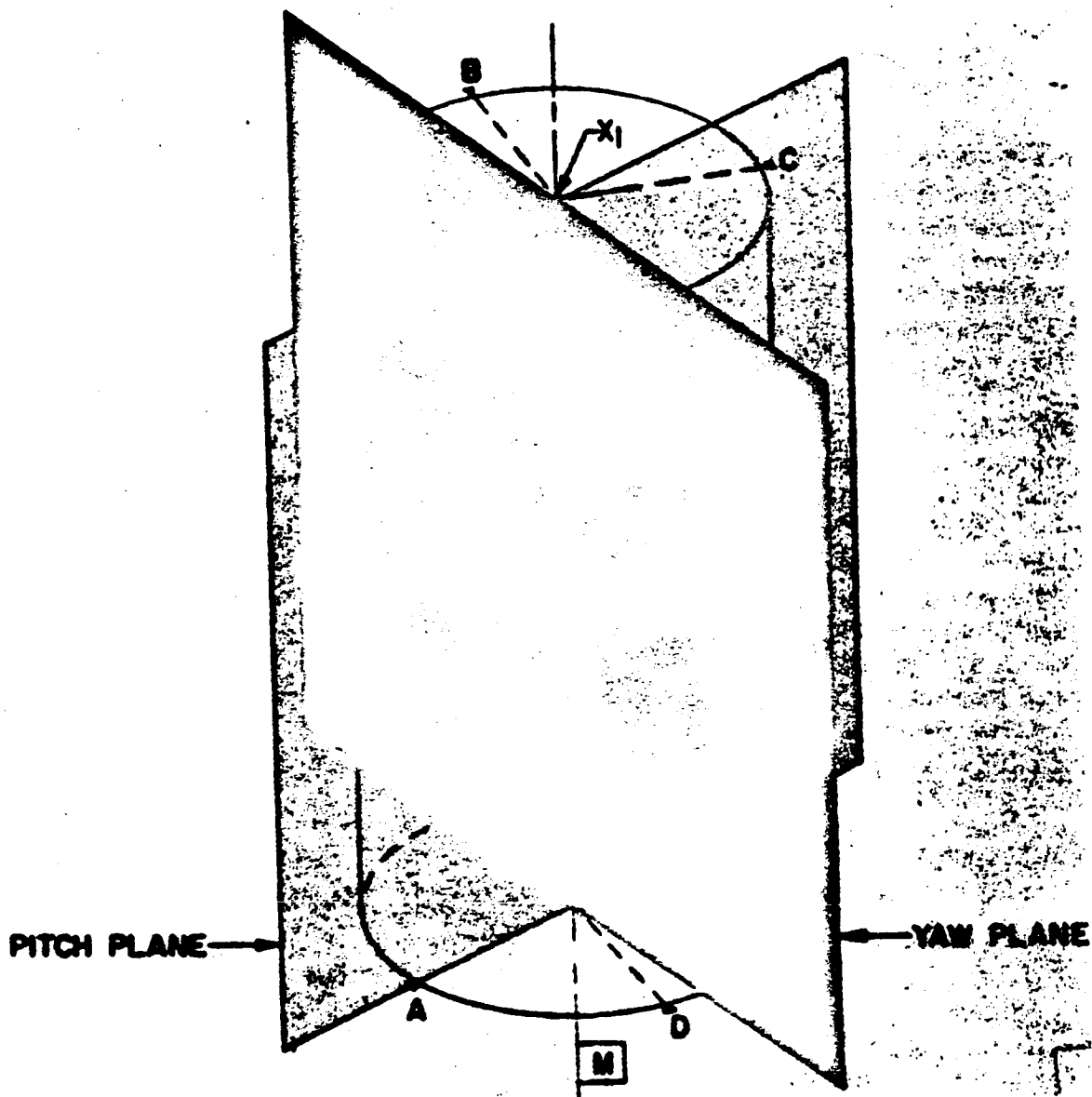


Figure 2-10. Basic Stage Reference, Vertical Assembly

## **SECTION III. CALIBRATION AND TEST OF OPTICAL TOOLING INSTRUMENTS**

### **A. Introduction**

The purpose of this section is to describe a standard process for alignment and calibration of optical alignment instruments. This procedure, as included in this document is in compliance with NPC 200-2 and NPC 200-3.

This procedure provides guidelines for the alignment and calibration of optical alignment instruments and specifies standards for alignment and calibration equipment.

### **B. Definitions**

For the purpose of this procedure, the following definitions shall apply:

(1) Calibration - Comparison of a measurement standard or instrument of known accuracy with another standard or instrument to detect, correlate, report, or eliminate by adjustment any variation in the accuracy of the item being compared.

(2) Measuring and test equipment - All devices used to measure, gage, test, inspect, or otherwise examine items to determine compliance with specifications.

(3) Reference measurement standard - Standards of the highest accuracy order in a calibration system which establish the basic accuracy values for that system. These are primary standards.

(4) Transfer measurement standard - Designated measuring equipment used in a calibration system as a medium for transferring the basic values of reference standards to lower echelon transfer standards or measuring and test equipment. These are secondary standards.

(5) Standard - Any piece of equipment established as a reference model.

(6) Direct - Reading with the telescope in its normal position.

(7) Reversed - Transit 180 degrees and traverse 180 degrees.

(8) To traverse - Move the line of sight left or right around the azimuth axis.

(9) To transit - To turn the telescope in a vertical plane about the horizontal axis.

(10) To rotate - To move the telescope on an axis that almost coincides with the line of sight.

### **C. Responsibilities**

The implementation of this procedure shall be the responsibility of MSFC and associated contractors. The Quality and Reliability Assurance Laboratory of MSFC shall be responsible for assuring that the requirements of this procedure are met.

### **D. Procedures**

#### **1. Measurement Standards**

Calibration shall be against certified standards which have known valid relationships to National Standards.

Values, having a known valid relationship to National Standards, may be obtained by using individually or in combination any of the three following methods:

(a) Values based upon natural physical constants.

(b) Values obtained by ratio type self-checking tests.

- (c) Values obtained by comparison to certified transfer measurement standards.

Within the state-of-the-art limitations, the error in the standards used in the calibration of any instrument shall be less than ten percent of the instrument's allowable error.

The instrument shall be adjusted, if any adjustment is needed, so that its error, within the state-of-the-art limitations, is less than ten percent of the tolerance of the item being measured.

## 2. Test Equipment

The equipment used in these testing procedures shall consist of four collimators, two scales, a stride level, and an elevating column mounted on a rigid framework that is supported by three shock-mounted columns. The optical devices are mounted on the framework as shown in Figure 3-1.

Collimator A (Figure 3-1) shall have a paired line type infinity reticle with a horizontal scale. It shall also have six additional reticles located optically at various distances from 0 to 100 feet. Collimator A must be designed so it can be leveled to required accuracy using the stride level and shall be mounted so that its direction can be adjusted a few degrees in the horizontal and vertical planes.

Collimator B shall have a paired line type infinity reticle and an eyepiece.

Collimators C and D shall have paired line type infinity reticles with horizontal scales.

The vertical scale E and the horizontal scale F shall be finely divided scales and their accuracy shall be verified by comparison to certified transfer standards.

The column I shall have a standard 3.5 inch diameter, 8 threads per inch male stud to accommodate standard mounting brackets of the instruments to be tested. The position of column I shall be on the line defined by collimators A and B.

The stride level shall be an accurate level which has been compared to a certified standard.

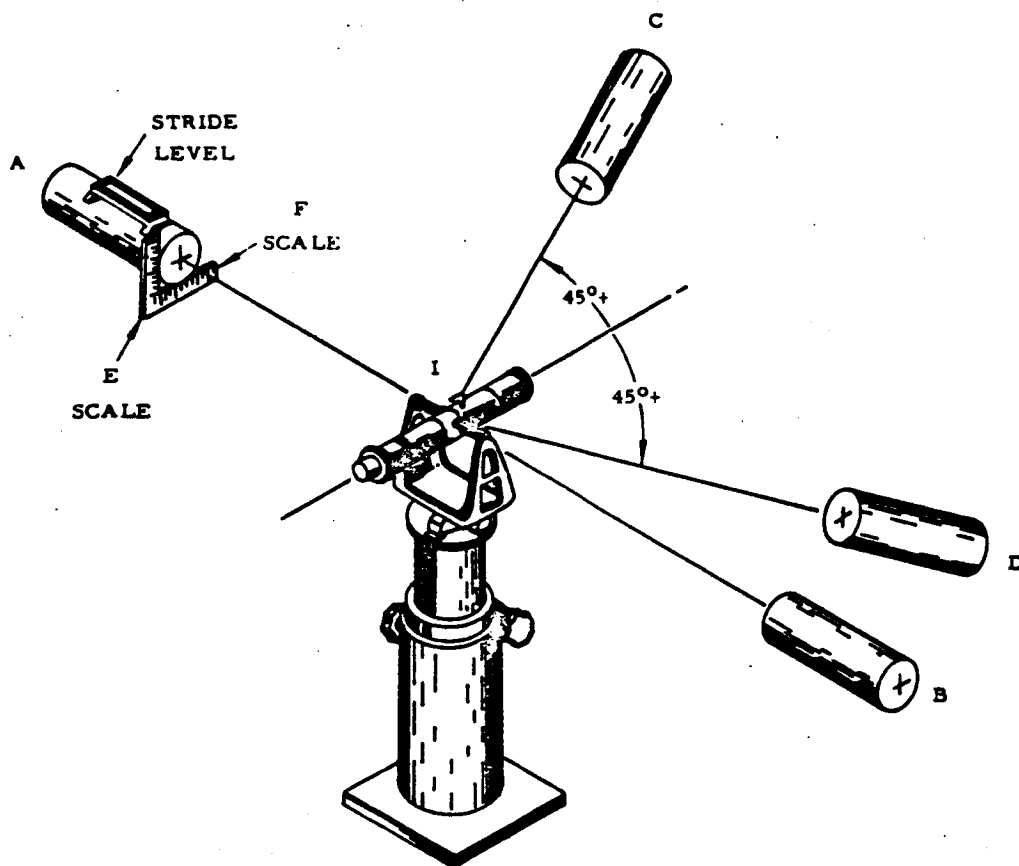


Figure 3-1. Principle Arrangement of the Collimator Test Stand

Collimators should be calibrated prior to use. Infinity focus of all collimators must be proven. The most accurate method utilizes three collimators. Collimator A is collimated with collimator B. The two are then tested for parallax to insure most accurate focus. Then collimator C is collimated to collimator A and tested for parallax. Finally, collimator C is collimated with collimator B. If no parallax exists, all three collimators must be at infinity focus. If collimator A is plus and collimator B is minus the same amount, they will appear to be perfectly collimated. However, collimator C would have to be minus by the same amount as collimator B to collimate with collimator A. In which case, it would not collimate with collimator B. Parallax would exist between collimators B and C.

The test equipment is used to determine the geometrical relationship between the optical and the mechanical systems of the instrument being tested.

If the tests reveal that any incorrect relationship exists, the test shall be repeated several times. A correcting adjustment shall be made only if repeated testing shows that the adjustment is necessary.

The adjustments will have less effect on each other if the tests and adjustments are made in the order given in paragraphs 3 through 6. However, since all interaction between adjustments cannot be eliminated by sequence, after any adjustment, tests already conducted shall be repeated.

### 3. Testing of A Jig Transit

Test 1 - This test, made to determine the presence of play in the supports, shall be conducted as follows:

(1) Mount the instrument on the post at I (Figure 3-1) and collimate with collimator A. Apply enough force at the base plate, the leveling head, the alidade, and the side of the telescope to cause the instrument to go out of collimation.

(2) If the instrument returns to collimation after the force is removed, there is no play in the supports.

(3) Failure to return to collimation indicates excessive play in the supports.

Test 2 - This test, made to determine the relationship between the plate level, or levels, and the azimuth axis, shall be conducted as follows:

(1) Mount the instrument on the post at I (Figure 3-1) and adjust the leveling screws until the bubble of the level being considered is centered.

(2) Traverse the head of the instrument 180 degrees and note the position of the bubble. If the position of the bubble has not changed, no adjustment is necessary.

(3) If the position of the bubble has changed, adjust the vial adjusting screws until the bubble has moved toward the center one half the distance that it was displaced.

Test 3 - This test, made to determine the relationship between the vertical crosshair and the elevation axis, shall be conducted as follows:

(1) Mount the instrument on the post at I and aim it at the center of the infinity reticle of collimator A.

(2) Move the telescope up and down with the tangent screw. No adjustment is necessary if the same point remains on the vertical crosshair.

(3) If the same point does not remain on the vertical crosshair, adjust the reticle by rotating.

#### NOTE

This adjustment will affect adjustments of tests 4 and 5.

Test 4 - This test, made to determine the relation between the line of sight and the horizontal axis, shall be conducted as follows:

(1) Mount the instrument on the post at I (Figure 3-1) and collimate it with collimator A. Transit the telescope 180 degrees and note the relationship between the vertical pattern of collimator B and the vertical line on the telescope.

(2) Traverse the alidade 180 degrees and repeat (1). No adjustment is necessary if the vertical relationship is the same as in (1).

(3) If the vertical relationship is not the same in (1) and (2), remove one-fourth of the difference by adjusting the reticle.

## NOTE

This adjustment will affect adjustments of tests 3 and 5.

Test 5 - This test, to determine if the line of sight passes through the horizontal axis, is made if the telescope's attachments include a reversion level, an autoreflexion target on the objective, or a target on the horizontal axis that has markings indicating the center of the axis. This test shall be conducted as follows:

- (1) Mount the instrument on the post at I (Figure 3-1). Point the telescope at the infinity reticle of collimator A and center the horizontal line. Focus on scale E and observe the reading.
- (2) Reverse the instrument and repeat (1). If the reading on scale E is the same as in (1), no adjustment is necessary.
- (3) If the reading on scale E is not the same in (2) as in (1), refer to the manufacturer's manual to obtain the proper procedure for adjustment.

## NOTE

This adjustment will affect adjustments of tests 3 and 4.

Test 6 - This test, made to determine the relationship between the horizontal axis and the vertical axis, shall be conducted as follows:

- (1) Mount the instrument on the post at I (Figure 3-1) and collimate the vertical line with the vertical line of collimator C. Transit the telescope until it is pointed at collimator D. Note the relationship between the vertical line in the telescope and the vertical line of collimator D.
- (2) Turn the instrument 180 degrees about its azimuth axis and repeat all of (1). No adjustment is necessary if the relationship between vertical lines is the same as in (1).
- (3) If the relationship between the vertical lines is not the same in (2) as in (1), remove one-fourth of the difference by adjusting one horizontal bearing block.

**Test 7** - This test, made to determine if the line of sight passes through the vertical axis, shall be conducted as follows:

- (1) Mount the instrument on the post at I (Figure 3-1) and collimate the vertical line with collimator A. Focus on scale F and note the reading.
- (2) Reverse the instrument and repeat (1). If the reading on scale F is the same as in (1), no adjustment is necessary.
- (3) If the reading on scale F is not the same in (1) as in (2), remove one-half the difference by adjustment. Refer to the manufacturer's manual to obtain the proper procedure for this adjustment.

**Test 8** - This test, made to determine if the telescope level bubble is in the center when the line of sight is horizontal, shall be conducted as follows:

- (1) Level collimator A.
- (2) Mount the instrument on the post at I and collimate the horizontal line with collimator A. No adjustment is necessary if the bubble of the telescope level is centered.
- (3) If the bubble is not centered, adjust the vial adjusting screws until the bubble is centered.

**Test 9** - This test, made to determine the relationship of the axle mirror or mirrors with the horizontal axis, shall be conducted as follows:

- (1) Mount the instrument on the post at I (Figure 3-1). Auto-collimate collimator B with the mirror whose surface direction is to be tested and note the vertical line.
- (2) Transit the telescope 180 degrees. No adjustment is necessary if the vertical line is in the same position as it was in (1).

(3) If the vertical line is not in the same position in (1) and (2), remove one-half of this difference by adjusting the mirror.

(4) Transit the telescope 90 degrees and repeat (1). If the reflection of the vertical line is centered, no adjustment is necessary.

(5) If the reflected image of the vertical line is not centered, move it to the center by adjusting the mirror.

Test 10 - This test, made to determine if the line of sight of the cross telescope coincides with the horizontal axis, shall be conducted as follows:

(1) Mount the instrument on the post at I (Figure 3-1) and collimate the cross telescope with the vertical line of collimator A or B.

(2) Transit the main telescope 180 degrees and note vertical line of cross telescope. No adjustment is necessary if the vertical line is still collimated with the collimator used in (1).

(3) If the vertical line is not collimated, remove one-half the difference by adjusting the cross telescope.

(4) Transit the telescope 90 degrees. If the vertical line is centered, no adjustment is necessary.

(5) If the vertical line is not collimated, remove the difference by adjusting the cross telescope.

Test 11 - This test, made to determine the straightness of the line of sight in the horizontal plane, shall be conducted as follows:

(1) Mount the instrument on the post at I (Figure 3-1) and point the telescope at collimator A.

(2) Turn the reticle patterns of collimator A to the horizontal position and center the horizontal line of the instrument's telescope.

(3) Focus on the objective lens of collimator A and move the instrument's telescope until it is almost centered.

(4) Recollimate the instrument's telescope with the infinity reticle of collimator A.

(5) Change the focus of the instrument's telescope to bring each of the other reticles of collimator A into focus. As each reticle is brought into focus, measure, with the instrument's displacement micrometer, the difference between the instrument's horizontal line and the collimator's horizontal line. Make 10 measurements for each reticle in collimator A.

(6) Rotate collimator A 180 degrees about its line of sight and repeat (2), (3), (4), and (5).

(7) Compute the average of the 20 measurements associated with each focus distance.

(8) Construct a graph by plotting each of these averages against its associated focus distance.

Test 12 - This test, made to determine the straightness of the line of sight in the vertical plane, shall be conducted as follows:

(1) Mount the instrument on the post at I (Figure 3-1) and point the telescope at collimator A.

(2) Turn the reticle patterns of collimator A to the vertical position and center the vertical line of the instrument's telescope.

(3) Focus on the objective lens of collimator A and move the instrument's telescope until it is almost centered.

(4) Recollimate the instrument's telescope with the infinity reticle of collimator A.

(5) Change the focus of the instrument's telescope to bring each of the other reticles of collimator A into focus. As each reticle is brought into focus, measure, with the instrument's displacement micrometer, the difference between the instrument's vertical line and the collimator's vertical line. Make 10 measurements for each reticle in collimator A.

(6) Rotate collimator A 180 degrees about its line of sight and repeat (2), (3), (4), and (5).

(7) Compute the average of the 20 measurements associated with each focus distance.

(8) Construct a graph by plotting each of these averages against its associated focus distance.

#### 4. Test of an Alignment Telescope

Test 1 - This test, made to insure that the vertical crosshair is truly vertical, is made as follows:

- (1) Mount the alignment telescope in V blocks.
- (2) Suspend a weight by a thin thread. Immerse the weight in oil.
- (3) Aim the telescope at the thread.
- (4) Mount a cross-level on the telescope.
- (5) Rotate the telescope until the bubble in the crosslevel is centered.
- (6) Reverse the level. The bubble should be centered.
- (7) If the bubble fails to center, adjust the level so the bubble moves halfway from its position to the level position.

(8) After adjusting and testing the cross-level, the bubble should be centered by rotating the telescope. The vertical cross-hair should be parallel to, or coincide with the weighted thread.

(9) If adjustments are necessary, loosen the reticle and adjust the telescope hairline to coincide with the weighted thread.

Test 2 - This test, made to determine the diameter of the sphere, is performed as follows:

(1) Measurements, using an accurate micrometer, should be made in several positions around the sphere and at various angles.

(2) Sphere diameter should be 3.5000 to 3.5005 inches.

Test 3 - This test, applicable when the sphere is part of the instrument, is conducted to determine if the line of sight is parallel to the axis of rotation of the alignment telescope.

(1) Mount the telescope in a cup mount and bracket, and collimate with collimator A.

(2) Rotate the telescope 180 degrees.

(3) The crosshairs should remain on the target.

(4) If the crosshairs do not remain on the target, refer to manufacturer's manual, and adjust until one-half of displacement is removed.

(5) Repeat tests (1) through (3) at various angles of rotation.

Test 4 - This test, applicable when the sphere is part of the instrument, to determine if the line of sight of the telescope coincides with the axis of rotation, is made as follows:

(1) Support the telescope by a sphere in a cup mount and by its tube in a bracket.

(2) Aim the telescope at a near target in collimator A with both optical micrometers at zero.

(3) Rotate the telescope 180 degrees. The cross-hairs should remain on the target.

(4) If adjustment is required, refer to manufacturer's manual. After any adjustment, repeat steps (1) through (3).

(5) Repeat steps (1) through (4) at various angles of rotation.

Test 5 - This test, applicable in all cases except that in Tests 3 and 4, is to determine if the line of sight is parallel with the axis of rotation of the telescope tube.

(1) Support the tube in V blocks and prepare tests and adjustments as in test 3.

(2) If the requirements of tests 3 and 5 cannot be satisfied simultaneously, the sphere is not centered on the telescope tube.

Test 6 - This test, applicable in all cases except that in Tests 3 and 4, is to determine if the line of sight coincides with the axis of rotation of the telescope tube.

(1) Support the tube in V blocks.

(2) Perform tests and adjustments as in test 4.

(3) If requirements of tests 4 and 6 cannot be satisfied simultaneously, the sphere is not centered on the telescope tube.

Test 7 - This test is to check the run of the micrometer.

(1) Set the micrometer at extreme low end of scale.

(2) With the leveling screws, sight a graduation on scale E or F.

(3) Turn the micrometer to zero and to plus 0.050 inch successively.

(4) The scale readings should be whatever the lowest scale reading is and the lowest reading plus 0.050 respectively.

Test 8 - This test is to determine the straightness of the line of sight of a telescope. From a practical viewpoint, the only method of performing this test is with a straightness of line of sight collimator. To perform this test, repeat test for determining straightness of line of sight in vertical plane (see paragraph 3, Test 12). Also repeat test in Test 12 for horizontal plane.

(1) The average of the 20 readings on each target should be computed and plotted against the length of sight each target represents. Draw a line connecting the points obtained from the horizontal micrometer reading. This line represents the shape of the line of sight in the horizontal plane.

(2) Draw a line connecting the point plotted for the nearest target to the point plotted for the farthest target. Departures from this line represent errors in straightness.

(3) Following procedure in (2) for the vertical plane will reveal any errors in the same manner.

#### 5. Testing of A Tilting Level

Test 1 - This test, to determine if the bubble of the circular level centers when the azimuth axis is vertical, is made as follows:

(1) Mount the level on the post at I (Figure 3-1) and rough level it by bringing the circular bubble to the center.

(2) Turn the level 180 degrees about its vertical axis. The bubble should remain level.

(3) If the instrument is not level after (2), remove half the difference with the adjusting screws and relevel.

(4) Repeat (2) and (3) until all errors are removed.

Test 2 - This test, to determine if the reticle is rotated, is made as follows:

(1) Point the telescope at collimator A. Adjust the stand so the telescope is near the center of the collimator.

(2) Focus the telescope on the infinity reticle in the collimator.

(3) Place the horizontal line of the telescope reticle in the center of the collimator reticle.

(4) Traverse the telescope slowly with the tangent screw and observe the horizontal line. It should cross the same point at the center of the collimator reticle. If it does not, the reticle will have to be rotated. Rotating the reticle will disturb all adjustments with the exception of the adjustment of the circular level.

Test 3 - This test, to make the main bubble center when the line of sight is horizontal and to check the accuracy of the micrometer, is conducted as follows:

(1) Point the tilting level telescope at the center of the infinity reticle in collimator A. The collimator must be level.

(2) With the horizontal line of the telescope centered on the horizontal pattern of the collimator, observe the fine level. The fine level should be centered.

(3) If the fine level is not centered, bring it to center by adjusting the level vial.

(4) If the tilting level is equipped with a displacement micrometer, compare the micrometer to the graduations of the scale at E.

.. . .

Test 4 - This test determines if the height of the line of sight is changed by errors in centering the bubble.

(1) Place a scale at collimator B. Point the telescope at the scale at E or F and change the position of the circular bubble by adjusting the leveling screws.

(2) Bring the bubble tangent to the circle on the same side as the scale being observed.

(3) Using the tilting screw, bring the fine level to center and note the scale reading.

(4) Turn the telescope 180 degrees about its axis, recenter the fine level and read the other scale. Find the difference in the two readings.

(5) Relevel the instrument so that the circular level bubble is tangent to the circle on the vial. Read both scales as in (4) bringing the fine level to center before each reading. Find the difference in the two readings. Their difference should be the same as the difference first noted.

#### NOTE

If the difference in readings are not the same, the tilt axis does not intersect the vertical axis. An instrument in this condition will introduce errors into the work.

Test 5 - This test is designed to determine the straightness of the line of sight in the tilting level.

(1) Turn collimator A so the reticle patterns are horizontal.

(2) Aim the tilting level telescope at the infinity reticle of collimator A and center the horizontal line.

(3) Focus on the objective lens of the collimator and move the telescope until it is almost centered.

- (4) Recollimate at infinity.
- (5) Change the focus of the telescope so the other reticles in the collimator can be brought into focus.
- (6) Using the displacement micrometer, take 10 readings at each of the other reticles at a distance greater than 50 feet, and 5 readings up to 50 feet. Average all readings.
- (7) Rotate the collimator 180 degrees. Recollimate and repeat the series of readings. Use the average for each position and average the readings for both tests. The true line of sight is the mean of both tests.
- (8) Using the values obtained in (6) and (7), plot a line on graph paper and compare it to a straight line. Any deviation will indicate inaccuracy in the telescope draw.

#### 6. Testing of a Theodolite

Test 1 - This test, made to check for play in leveling screws, is accomplished as follows:

- (1) Collimate telescope with collimator A (Figure 3-1) and apply force at each leveling screw.
- (2) Instrument should return to collimation when force is removed.
- (3) Refer to manufacturer's manual if adjustment is required.

Test 2 - This test, to determine centering of plate levels and to level instrument using the plate level, is accomplished as follows:

- (1) Turn instrument so the plate level is parallel to a line through centers of any two leveling screws. Bring bubble to center.
- (2) Turn 90 degrees so level is directly over third screw, and center bubble.

(3) Repeat (1) and (2) until bubble remains centered.

(4) From position (2) turn instrument 180 degrees in azimuth. Bubble should remain centered. If bubble does not remain centered, refer to manufacturer's manual for adjustment.

(5) After main level centers through complete rotation, observe position of circular level. It should be centered. If bubble is not centered, refer to manufacturer's manual for adjustment.

Test 3 - This test, made to insure vertical line of reticle is perpendicular to the transit axis, is accomplished as follows:

(1) Point theodolite at collimator A and collimate.

(2) Lock the vertical clamp.

(3) Using the vertical tangent screw, transit telescope so the entire vertical line of the reticle passes through the center of collimator A.

(4) The line should remain centered with the reticle pattern throughout its length.

(5) If it does not, the reticle must be rotated. Refer to manufacturer's manual for adjustments.

#### NOTE

Any adjustment under test 3 will affect adjustments of tests 4 and 5.

Test 4 - This test, to determine if the line of sight is perpendicular to the transit axis, is conducted as follows:

(1) Collimate with collimator A.

(2) Transit telescope 180 degrees and observe collimator B.

(3) Reverse instrument, recollimate with A.

(4) Transit and point at B. Vertical line of reticle should be in the same position with respect to reticle of B as before.

(5) Any difference represents four times actual instrument error.

Test 4 - (Alternate method)

(1) Collimate with collimator A. Set horizontal scale near zero and bring into coincidence with micrometer.

(2) Note micrometer reading.

(3) Reverse instrument and recollimate with A.

(4) Bring scale to coincidence.

(5) Note scale reading and micrometer reading.

(6) Subtract first reading from second reading. Any difference from 180 degrees is twice instrument error.

(7) Refer to manufacturer's manual for adjustments.

NOTE

Any adjustment under test 4 will affect adjustments of tests 3 and 5.

Test 5 - This test, to see that the line of sight is level when the vertical scale (Figure 3-2) reads horizontal and the split bubble is centered, is conducted as follows:

(1) Level collimator A.

(2) Collimate with collimator A and center horizontal line of reticle.

(3) Set vertical scale to read 90 degrees from zenith.

(4) Observe the split bubble. It should be centered.

(5) Refer to manufacturer's manual for adjustments.

## 7. Testing of Accessories

Accessories shall be checked for conformance to National Standards and this specification.

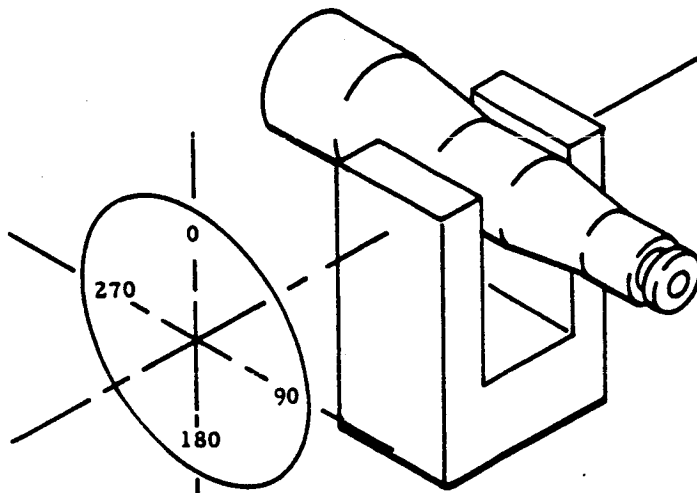
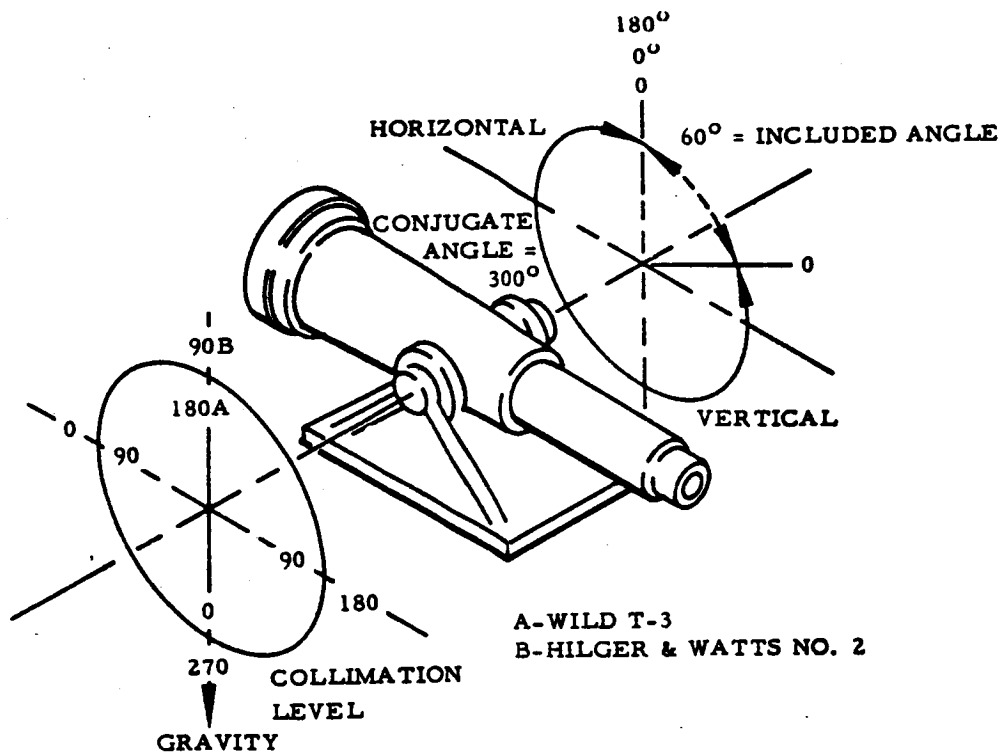


Figure 3-2. Vertical Scale Setup

## SECTION IV. OPTICAL TOOLING METHODS

The application of optical tooling instruments can be classified in three categories; the attached method, detached method, and a combination of the attached and detached methods. The method used is determined by type of work to be done. The purpose of this section is to describe these methods and by examples show their application.

### A. Attached Method

Fundamental instruments of the attached method are the alignment telescope, optical square, targets, spherical mounts, and mounting brackets. The mounting brackets have an adjustable cup mount to accommodate the spherical mounts. These spheres are made to AIA specifications by double facing a 3 1/2" sphere and boring a 2 1/4" hole through the center. This hole is a slip fit for the alignment telescope and targets. When the face of a target is at the center of this sphere, the sphere can be rotated without changing the center of the target. If an alignment telescope in a spherical mount is pointed at a target in a spherical mount, a line of sight is established.

The attached method is used when the cup mounts can be permanently installed on the work piece, and it is necessary to establish a line of sight in the same place more than once. For these reasons this method is used mostly in constructing large assembly fixtures or inspection fixtures. In designing tools of this type, lines of sight are used to establish the basic references of the end item. For example; if an assembly fixture is required to fabricate a missile fin, the fixture could be designed to have lines of sight establish the fin chord plane. All locators controlling fin configuration would be measured from these lines of sight. As a result the finished assembly would conform to design requirements.

Figure 4-1 shows the frame for an assembly jig. The first line of sight established, the basic line of sight, is the master control reference. All other lines of sight are located by measuring from it. In this example the basic line of sight is level. The position of the first mount is located by measuring from the frame to the center of the sphere. This is not a critical dimension. The only requirement is that sufficient clearance is allowed for the locators to be installed. This is also true of the spherical mount at B. These spheres, A and B, are brought to the same elevation with a sight level, by sighting targets or scales.

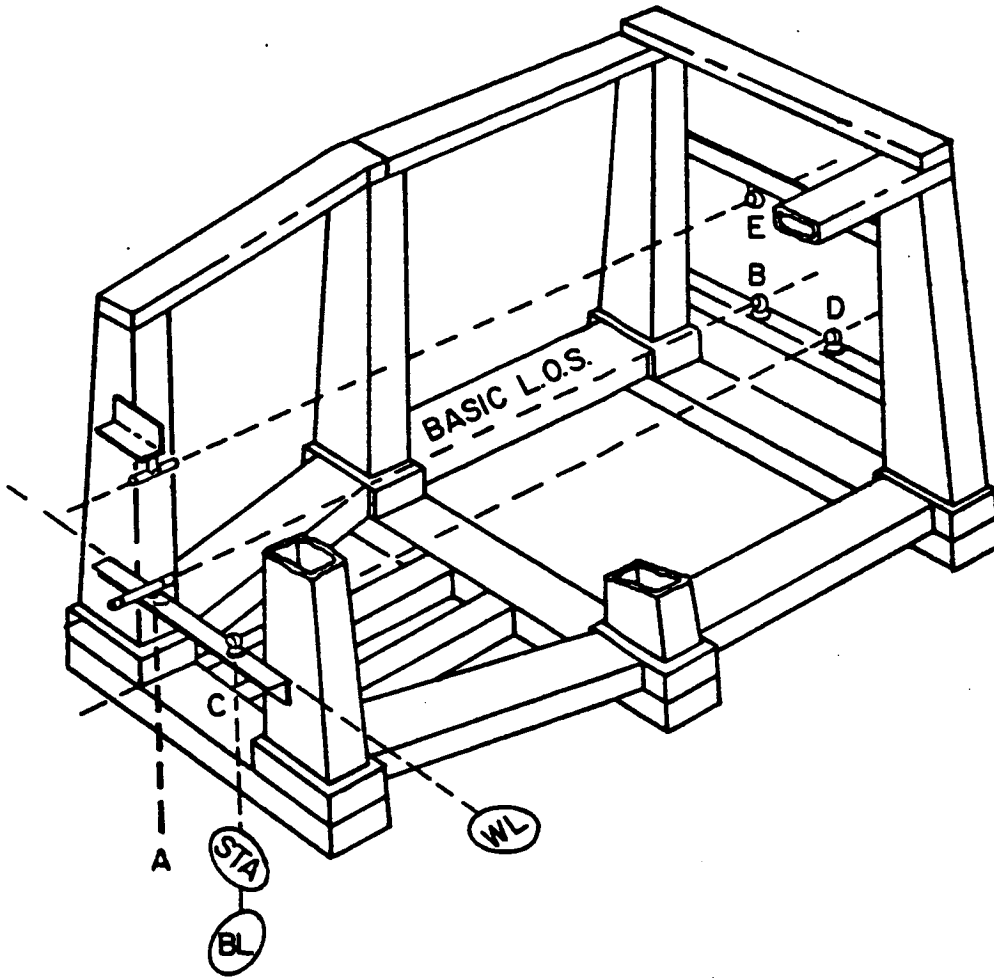


Figure 4-1. Assembly Jig Frame

Line CD is made parallel to AB by bucking in a transit, parallel to AB, between A and C. This is done by sighting scales, placed against spheres A and B, with a transit and aligning it with two corresponding readings. Then spheres C and D are positioned from this line in the same manner. Spheres C and D are brought into plane with A and B with the sight level.

In Figure 4-1, spheres A and C are on the same station plane. To bring C into station with A, the most accurate method is by the use of an optical square. The procedure for this will depend upon the type of optical square used. The easiest method is to have an

optical square that is built in a standard sphere and is designed for straight through as well as right angle sights. With this type of square installed on an alignment telescope, place the square in mount A so that the telescope is pointed on a target in mount B. Sight a target in mount C through the right angle aperture. Adjust C until it is in plane with A.

Line EF can be made parallel to AB by bucking a transit in on AB and positioning spheres at E and F to the plane of the transit. If E is to be on station with A and C, buck a transit in on AC and position E to its plane.

All lines of sight in the attached method can be located in a similar manner. Once the cup mounts have been positioned and secured the instruments can be removed. If the mounts are not disturbed the lines of sight can be reestablished by replacing the instruments in the mounts.

Where large parts or assemblies require close inspection and several units must be controlled the attached method should be considered. Inspection fixtures can be built with lines of sight arranged to measure almost any configuration. Measuring devices may be simple, such as scales, or for some requirement may be gages made to contact contours.

The attached method is accurate to the order of 1 arc second, and .001 inch. Once instruments are installed they can be easily replaced in their original positions. With the aid of gaging devices almost any configuration can be measured. But in order to utilize this method, sufficient lead time must be available to design necessary fixtures and related equipment.

## **B. Detached Method**

The detached method is the most versatile application of optical tooling. In this method instruments are set on stands or tooling bars. Fundamental instruments of this method are transits, sight levels, tooling bar stands, scales, and targets. In some applications theodolites are used. Theodolites will be treated in a later section.

Leveling large objects with a sight level and measuring differences in elevation is the least complex form of optical metrology. The sight level is set up on an instrument stand and leveled. This establishes a horizontal reference plane from which measurements can be taken. Using a properly designed scale, surface tables, machine tools, or large structures can be leveled to the order of one arc second.

The jig transit when properly leveled will establish vertical reference planes. In order to apply these planes to a measuring problem the plane must be perpendicular to the plane of the measurement. This can be accomplished in several ways, the easiest is to buck in the transit with the basic references of the work. Then measurements can be taken from the reference plane established by the transit to critical locations on the work. Range of measurements is limited by the length of scales available. Lengths longer than this can be measured using optical metrological tapes or tooling bars. Tapes with an accuracy of .005 inch can be obtained up to 300 feet long. Tooling bars are available in lengths up to 30 feet with an accuracy of .001 inch.

Figure 4-2 illustrates an example of the detached method. This setup was used to lay out a large casting prior to machining and to inspect the casting after machining. There are several principles of optical tooling incorporated in this example. It provides measurements in three mutually perpendicular planes, illustrates applications of auto-collimation, collineation and reticle projection.

This casting is an arc comprising  $1/4$  of a circle and weighs approximately 20 tons. It was to be machined on accurate 90 degree radial planes to fit three other quarter sections. Since the center of this circle is a point in space, optical methods were used to lay out the ends in relation to that point. The complete assembly also had two surfaces faced. These were layed out as elevations.

Since the layout and reinspection were required for several units, the tooling dock was of a permanent nature. The tooling bar on the left was set first. The only requirement for its position being that the bar was level and enough room left for the other bar and the part. Instruments used on the tooling bars were Brunson No. 75 transit squares. Alignment telescopes were used as control instruments at the ends of the bars; however, jig transits equipped for auto-collimation could have been used.

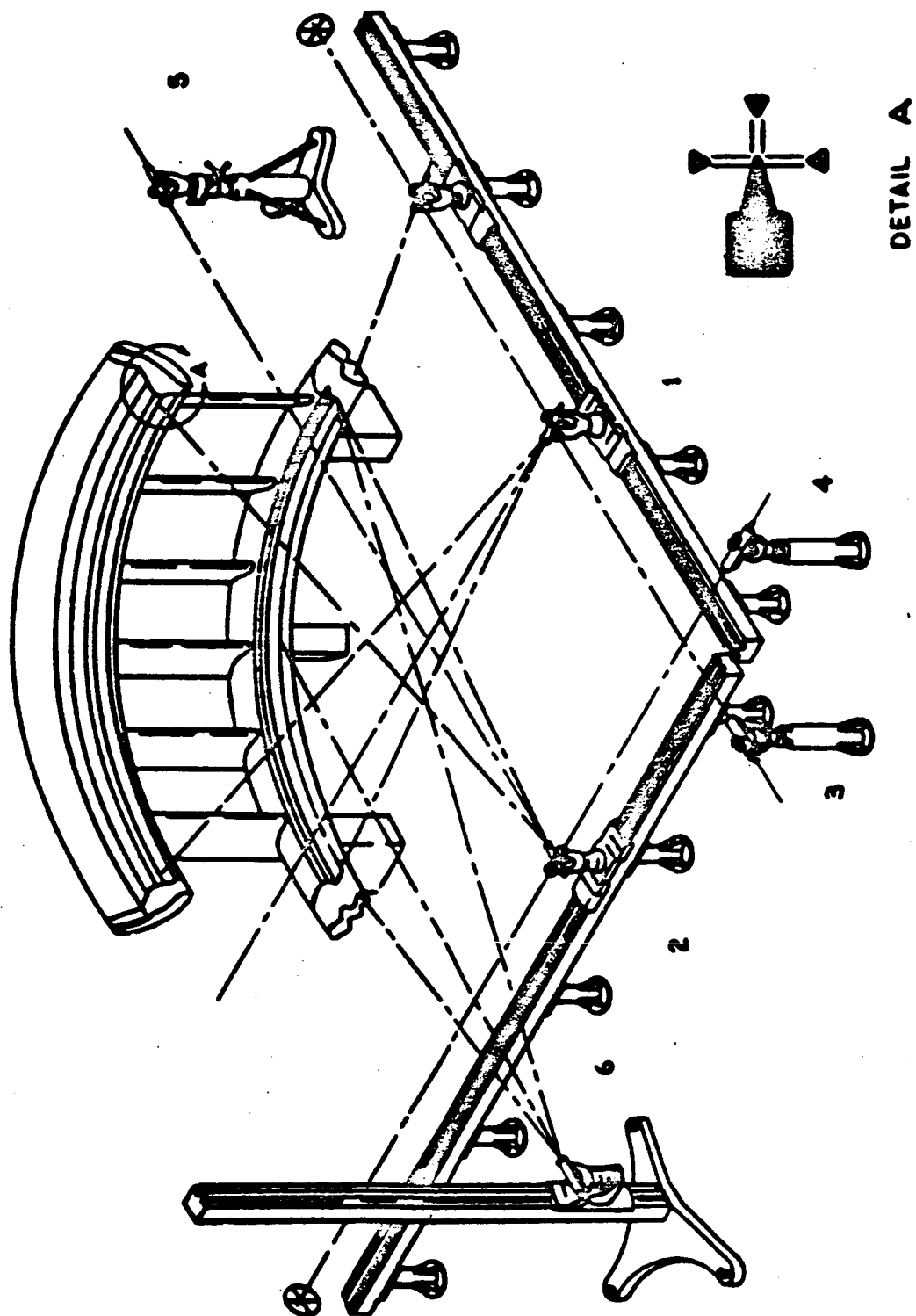


Figure 4-2. Detached Method

To set the control instrument for the first bar, the transit used was bucked in with the tooling bar index holes. It was then pointed at the alignment scope at position three and its telescope leveled. The transit telescope was collimated with the alignment scope. The target at the end of the tooling bar was then aligned with the alignment scope. This target serves as a reference to monitor the alignment scope.

Transit number one was then moved to the end of the tooling bar adjacent to its control instrument. Auto-collimating the alignment scope with the axle mirror of the transit positioned the transit telescope perpendicular to line of sight established by alignment scope. Tooling bar number two was then brought into alignment with transit number one. Alignment scope four was aligned with tooling bar two by transiting the telescope of transit one 180 degrees and collimating. To complete the set up of this tooling bar a second end target was aligned with scope four, and transit two auto-collimated with scope four.

With a setup completed as just described, mutually perpendicular, vertical planes can be established by the two transits. These planes can be established at any position within the length of the tooling bar with an accuracy of 0.002 inch. This provides a coordinate system of measurement in two axes. A third axis is added by the inclusion of a vertical tooling bar equipped with a sight level.

The casting to be layed out was positioned within the range of the tooling dock, as illustrated in Figure 4-2 and rough leveled. Transits one and two were positioned at a convenient point on their tooling bars and auto-collimated to their respective alignment scopes. Steel tapes were held against the ends of the casting on the inside edge and read from transits one and two. The casting was rotated until the readings on the tapes were the same. The intersection of the lines of sight was then the center of radius of the casting. The casting was then leveled to required accuracy.

Reticle projection was decided upon as being the best method of laying out the material to be removed. When an instrument is focused on an object, the reticle pattern forms a weak image on the object. If a light of sufficient intensity is reflected through the reticle, the reticle pattern can be seen on the object. This requires a special reticle and light source. To mark the casting, a pointed piece of steel was welded on so that the point protruded beyond the center of the reticle image. See detail A Figure 4-2. This point was then filed to the center of the

image. To transfer the layout to the other side of the casting, transit five was collimated with transit one and its reticle projected. Then transit five was moved and collimated with transit two and the process repeated. Elevations were laid out in a similar manner using the level on the the tooling bar.

### C. Combination of Attached and Detached

Some applications may require a combination of the attached and detached methods. Figure 4-3 illustrates the construction of a tooling fixture. The cup mounts would be positioned as described under attached method. Next, the tooling bar and its control instrument must be made parallel to the basic line of sight. This could be accomplished by bucking in a transit on scales placed against the spherical mounts. Next the tooling bar could be aligned with this transit. The transit could be used as a control instrument. If another instrument would be better as a control instrument it could be collimated with the transit. Next, a target should be aligned with the control instrument as a reference. Then with a transit square mounted on the tooling bar, measurements could be taken perpendicular to the basic line of sight.

This section has described the three methods of applying optical tooling instruments. Descriptions have been of a general nature, not in detail. The details, however, are important. They must be fully understood in order to make accurate measurements. Because of the importance of these fundamental operations they will be described in detail.

### D. Fundamentals

#### 1. Leveling

Most instruments have a spirit level as a gravity reference. To level an instrument this level is brought to center. On transits and some levels the bubble is centered by moving the vertical axis of the instrument into a vertical position. On tilting levels the vertical axis is adjusted nearly vertical using a rough level and the line of sight is made horizontal before each reading by bringing the split bubble to coincidence. To accurately level an object using a telescope in conjunction with a spirit level, the telescope should be positioned so that all sights are the same length. If this cannot be

done, two instruments should be used in such a manner that a short sight of one coincides with a long sight of the other and long sight of the first with a short sight of the second. The average of the results should be used.

## 2. Bucking In

The term buck-in refers to aligning a transit with two points. The points may be in front of the instrument or one in front and one in back. In either case the instrument is pointed at the far point by traversing about its vertical axis, and to point at the near target the axis itself is moved.

### a. Bucking In With Both Points on One Side of Transit

- (1) Set the instrument stand on which the transit is to be mounted in as correct a position as possible by eye. Adjust stand to desired height.
- (2) Position lateral adjuster on instrument stand perpendicular to reference points to be aligned.
- (3) Carefully remove the instrument from its carrying case. It will either be packed horizontally in an insulated case, or vertically screwed onto a base plate which will slide in or out of the case. When it is packed vertically, slide the baseplate out of the case and release horizontal clamping screw so that the instrument base will rotate freely for unscrewing. Hold standard in one hand, and use other hand to unscrew the instrument.
- (4) Mount the instrument on the lateral adjuster.
- (5) Try all clamps and movements to be sure there is no binding. Do not force anything.
- (6) Center the lateral adjuster on the stand so that it is perpendicular to the line of sight of the transit when the transit is pointed in the direction to be used.

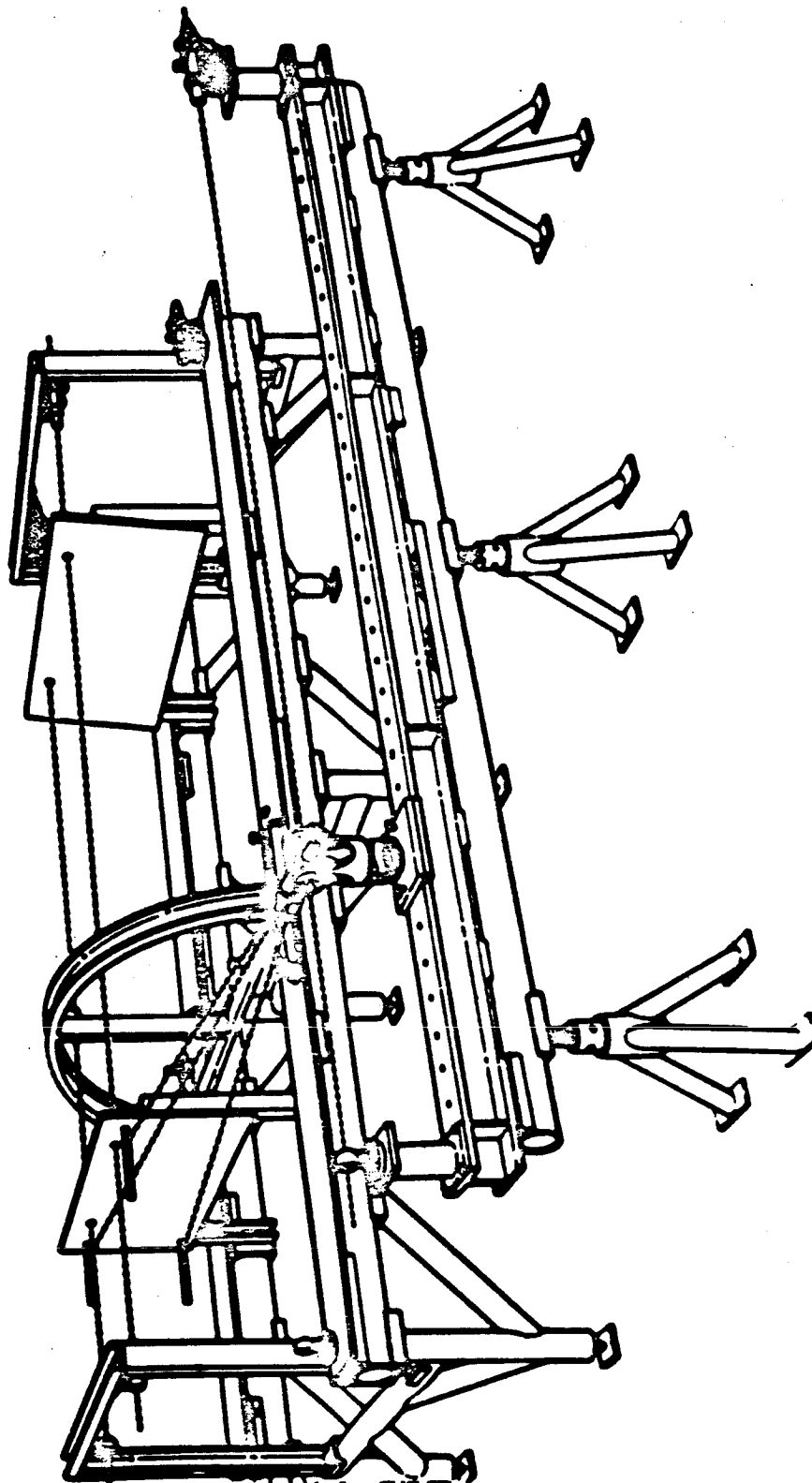


Figure 4-3. Tooling Fixture

## CAUTION

Ensure that mounting surfaces are wiped clean before mounting instrument. This is to avoid grit, filings, etc., from damaging threads and preventing flush seating of the instrument on the flange on which it should rest.

(7) Never move stand with the instrument attached.

(8) Rough level the instrument as follows:

(a) Position the telescope so that it is parallel to two opposite leveling screws.

(b) Center the plate level vial parallel to two leveling screws. Adjust these two screws to bring into level. Opposite screw must be turned in opposite direction at the same time so as to maintain equal pressure on the base plate at all times. Avoid too great or too little tension. Too much tension will distort the base plate; not enough tension will result in an unstable instrument.

## NOTE

Some makes of transits have a circular level vial and other models have two level vials.

(c) Center the plate level vial over the other two leveling screws and adjust for error in the same manner.

(d) Repeat (b) and (c) as necessary until instrument is rough leveled.

(9) Align the telescope with the far and near reference points.

(a) Focus on the far point.

(b) Lock both horizontal and vertical clamping screws. Use the horizontal tangent screw to align the vertical crosshair exactly on the reference point. Check for parallax.

(c) Leave horizontal clamping screw locked but loosen the vertical clamping screw. Refocus the telescope on the near reference point. It will almost certainly not be aligned with the vertical crosshair.

(d) Move the transit by adjusting the lateral adjuster until the near point is aligned. Note on the scale the distance you moved it. Now move it as much farther as you judge it should go. Experience will develop skill in judging how far to move the lateral adjuster depending on relative distances between the reference points and the transit.

(e) Free the telescope in both planes and refocus on the far reference point.

(f) Repeat steps (c), (d), and (e) until transit is aligned.

(10) Checking geometry.

(a) Transit and rotate instrument.

Transit by rotating the telescope on the horizontal axis  $180^\circ$ . Rotate by moving the instrument around the vertical axis  $180^\circ$ .

(b) Align the instrument with the near reference point.

(c) Focus on the far reference point.

(d) Measure any misalignment on the micrometer. If micrometer shows geometry off, send the instrument to the calibration laboratory.

(11) Fine level the instrument.

(a) Position the telescope over two diagonally opposite leveling screws normal to line of sight and center the telescope level vial.

(b) Lock the vertical clamping screw and use the vertical tangent screw for fine adjustment to level the telescope.

(c) Rotate the telescope horizontally 180° with the vertical clamp still locked. Fine level again by removing half the error with the vertical tangent screw and the other half with the two leveling screws that are parallel to the telescope. Return to original position and repeat as necessary until the level remains perfectly centered in both positions.

(d) Rotate the telescope 90° across the other two leveling screws and remove any error noted by adjusting the foot screws only.

(e) Make a final check of the level in various positions around the compass. (Unlike the optical level, a transit must be level in all directions in order to sweep a vertical plane.)

(12) Check the reference points for alignment. The fine leveling procedure may have disturbed this alignment. If so, repeat steps (9) and (11) as necessary.

b. Bucking In With One Point on Each Side of Transit

- procedure a.
- (1) Complete steps (1) through (8)
  - (2) Align telescope with reference points.
    - (a) Focus on either of the two points.
    - (b) Lock horizontal clamping screw. Use the horizontal tangent screw to align the vertical cross-hairs exactly on the reference point number one, and check for parallax.
    - (c) Transit telescope 180° and focus on reference point number two. It probably will not be aligned. Check for parallax. Move the transit by adjusting the lateral adjuster one half distance to reference point number two.

## NOTE

If the distance from each point to the transit is equal, one half is the correct amount of lateral movement; if not, it must be moved in proportion to the distance from the reference points to the transit.

(d) Transit telescope  $180^\circ$  and focus on reference point number one; bring vertical crosshair exactly on with tangent screw. Repeat steps (2) (a) through (2) (d) until no error is detected.

(3) Checking geometry.

(a) Rotate by moving the transit around the vertical axis  $180^\circ$ .

(b) Align the instrument with one reference point.

(c) Transit instrument telescope  $180^\circ$  and measure any vertical misalignment with the optical micrometers. If micrometer shows geometry off, send the instrument to the calibration laboratory.

(4) Fine level the instrument by following steps (11) and (12) of procedure a.

### 3. Collimation

To collimate two telescopes makes their optical axis parallel using the behavior of parallel light. With a lens or lens system the focal point is the point where light that is parallel to the optical axis is focused. The focal plane is perpendicular to the optical axis passing through the focal point. If a telescope is focused to infinity, that is focused for parallel light, any image produced by parallel light will be in focus on the focal plane. A telescope can be set on infinity using a mirror that is flat to the order of one-quarter light wave. To focus to infinity, illuminate the reticle and place the mirror over the objective. Focus the instrument until a reflected image of the reticle is in focus. To collimate two telescopes, focus one to infinity as just

described. Leave the light on and remove the mirror from the objective. Point the second telescope toward the first, near the center of the objective. Focus the second telescope toward infinity until the reticle of the first is in focus. Adjust the pointing of the second telescope to coincide with the reticle of the first by changing the angle between them. Parallel light is not sensitive to displacement, only angular movement will change the relative position of the image.

#### 4. Collineation

Collineation of two telescopes is achieved when their lines of sight occupy the same space. For most purposes one is only concerned with one plane at a time. For example, if measurements are to be taken with respect to a vertical plane the horizontal plane is of no significance. Two transits are considered collineated when their vertical planes of sight coincide. Collineation is accomplished by first collimating to make the lines of sight parallel. Then focusing both telescopes on a common target, adjust by lateral movement until both lines of sight coincide with the target. Next, recollimate at infinity focus and adjust angular relationship at short focus displacement. The best target for collineation is the reticle pattern of one telescope. To collineate using the reticle as a target collimate as before. Next, turn the focusing knob away from infinity until the other telescope is in focus and continue until the instrument is focused at some point midway between the telescopes. Illuminate the reticle of the first instrument and shorten the focus of the second telescope until the reticle of the first is in focus. If the reticles do not coincide move the second telescope laterally until they do. Recollimate and repeat the procedure until both conditions are satisfied.

#### 5. Auto-Collimation

Auto-Collimation is the process of making a telescope perpendicular to a mirror. The telescope is pointed at the mirror and then focused to infinity. The reflected image of the reticle is made to coincide with the reticle by changing the angle between the mirror surface and the line of sight. When this is achieved the mirror is perpendicular to the line of sight. The mirror may be against a machined surface or on the axle of a transit. The later case is used to make the transit telescope perpendicular to the first telescope.

## 6. Auto-Reflection

Auto-reflection is used for the same purposes as auto-collimation. However, an auto-reflection target is required. This target is attached to the telescope on the objective end. In some cases it is placed on the cover glass. The telescope is pointed at the mirror and focused on the reflected image of the target on the telescope. Since the telescope is not focused at infinity, the micrometer can be used to measure any displacement between the reflected target and the reticle. If the graduations on the target are known and the distance from the instrument to the mirror is known this displacement can be converted into the angle between the mirror and telescope.

## SECTION V. PLANNING OPTICAL ALIGNMENT

Planning is a vital step in optical alignment. Whether this is a formal process documented by written procedures or is done as the job progresses someone has to do some planning. Usually this starts with a study of a drawing of the item. From the tolerance and basic reference system the best method of alignment can be determined.

There are several factors to be considered in selecting an alignment method. Among these are: size and shape of the item to be aligned, type of structure, tolerance, accessibility, lead time, and the basic reference system. In the planning phase each factor should be considered separately. Everything that is essential to any requirement should be noted. Then the method which best satisfies all requirements can be applied.

Every measuring and alignment problem is different, making it difficult to lay down rules for alignment procedures. This section will illustrate methods of planning these procedures, show the main areas of consideration, and the factors that affect them.

One advantage of optical tooling methods is that large components can be positioned and aligned to close tolerances. Of course, the adjectives large and close are relative and should be defined. For the purpose of this treatise, components having any dimension over 3 feet are large. Tolerance less than or including .01 inch; or 15 seconds of arc are close.

The first requirement of alignment is accuracy. So the first factor to consider in planning alignment is accuracy. In deciding upon instrumentation one should know instrument specifications and whether the instruments are within these specifications. This also applies to accessories because they are essential to any set up. Information relating to instrument accuracy can be obtained from instrument manufacturers and should be verified by a competent standards laboratory.

Properly designed targets are important to the extent to which they affect the accuracy of pointing. In tests, conducted at Princeton University in 1952, it has been found that the best target design has five fundamental characteristics:

(1) High contrast - Black on white gives the best contrast and is, therefore, almost always used for targets.

(2) No phase - If a target has phase an observer will point at different places under different lighting. Any target which is not on a flat background will have phase.

(3) Symmetry - If a target pattern is not symmetrical a telescope cannot be pointed at the same place each time.

(4) Proper area of reference - The target must have enough white area so the reticle can be placed in the center with the same amount of white showing on each side of the line. The amount of white showing on each side of the line should be about the width of the line to a maximum of three times the width of the line. For this reason, targets designed to be used over a range of distances have several sets of paired lines. The pair to use at a given distance is the one that meets the above conditions.

(5) Freedom from errors of orientation - To be free from errors of orientation a target must be designed so a telescope can be pointed at the center even though the pattern is rotated with respect to the reticle pattern.

The design found to be the best in all cases is the paired line target. A bullseye design is also good. An instrument can be pointed at the center of either of these within 0.5 second of arc.

The accuracy of pointing falls off rapidly when make shift targets are used. For example, scribe lines are sometimes used as targets. Assume a line to be 0.005 inch wide located 20 feet (240 inches) from the instrument. If the reticle line is 3 seconds wide at 240 inches it will cover 0.003 inch. Under these conditions the accuracy of pointing would be about 2 seconds and for greater distances would decrease even more.

Of course, the tolerance allowed must be taken into consideration. If the inaccuracy of pointing does not exceed ten percent of the tolerance and setting targets requires too much time, use the fastest method that will meet requirements.

Another factor that affects accuracy is the area in which the work is to be performed. Lines of sight must not be exposed to large sudden temperature changes. Mechanical traffic must be kept to a minimum. People not involved in the work should be kept out of the area. Proper lighting should be available. From 30 to 50 foot candles is about right.

Once a setup is made it should be possible to monitor it at all times. This is most important when good control of the area isn't possible. Several factors can change the alignment of instruments with each other or with reference points.

Another thing to be avoided in planning a setup is obstruction in the lines of sight. There must be a clear area from the objective lens of any instrument to any target the instrument will be pointed at. To check this, imagine a cone the size of the objective lens at one end and the target at the other connecting the telescope and the target. Nothing should be within this area. Anything obstructing this area will cut off light from one side of the target. The target as observed through the telescope will be displaced.

Another important factor to be considered during planning is safety of personnel and equipment. This includes using the proper equipment. Work platforms or lifts should be adequate for load. Personnel should have proper safety equipment. Leather soled shoes should not be allowed working above floor level. People who do not belong in work area should be kept out. Good housekeeping, of course, is always a necessary safety factor.

The time required to accomplish the job using different methods should be considered. There is usually more than one method to accomplish a task. If accuracy and safety are not sacrificed, the fastest method is the best method. Using a level and scales for elevations is faster than using a vertical tooling bar, until the distance to be measured exceeds range of scales. This is also true for lateral measurements with transits. For setups involving tooling bars the control instrument that is easiest to use should be used if it meets accuracy requirements. Having control of the area, the right number of people and instruments, and also the tolerance will affect the time requirement.

Some of the factors mentioned affect accuracy, safety, and speed. These are not entirely separate categories, but for preliminary planning should be considered as such and then combined.

Figure 5-1 is a drawing of a part. Following the method just described, plan the best method of checking the hole pattern in relation to the basic reference system.

1. What is the basic reference system of this part?
2. How can it be physically established?
3. What instrumentation would be required?
4. Describe or diagram the setup you would use.
5. What accuracy do you expect in your results?
6. How many people would be required?
7. How long will it take to check this using your method?

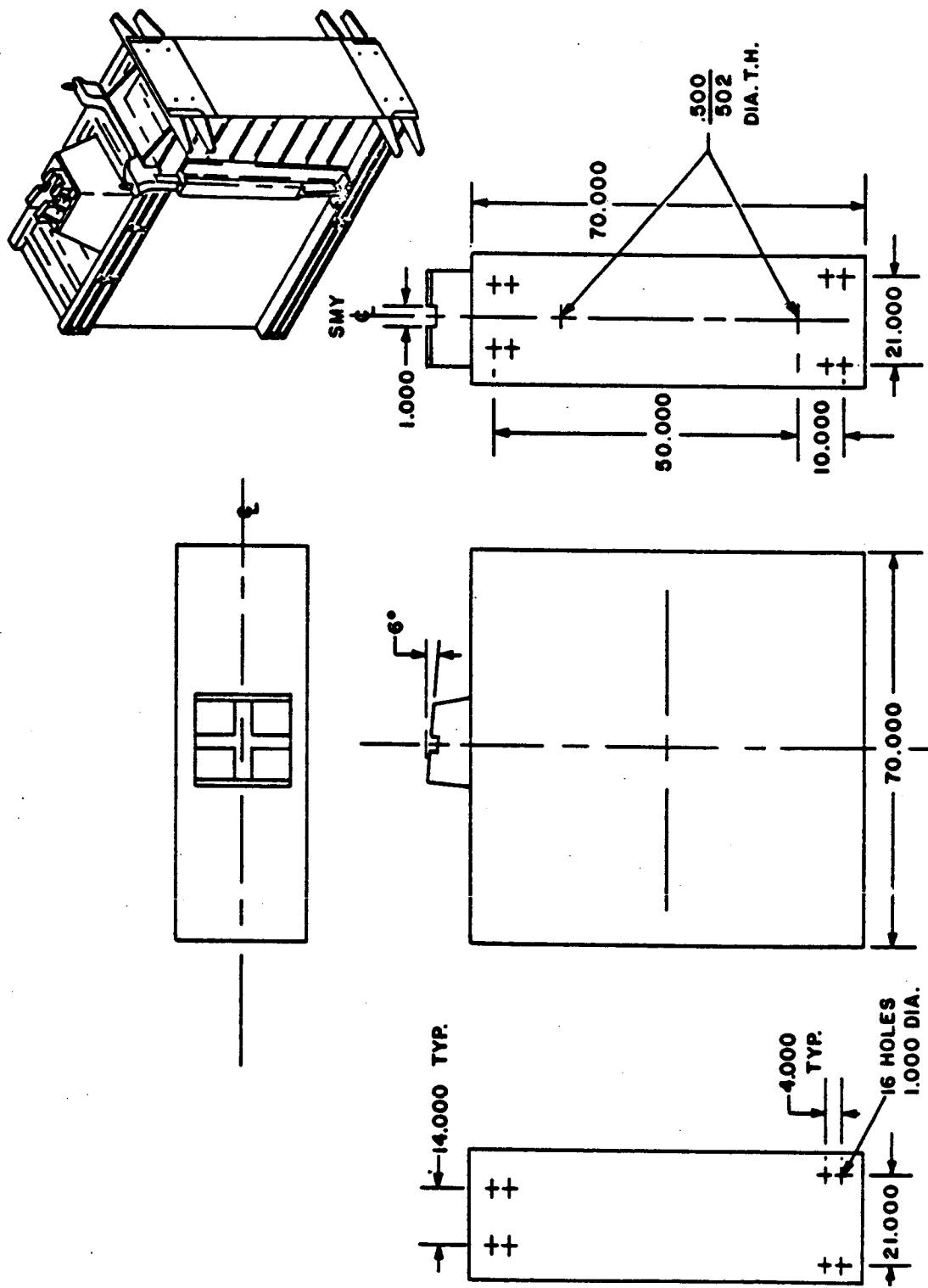


Figure 5-1. Planning Problem

## SECTION VI. JAW LAYOUT

Figure 6-1 is a sketch of a hold down jaw for the SI-C test stand. This part is approximately 7.5 feet long, 4.25 feet wide, and 10.0 inches thick. It is made of steel and weighs 6 tons. This jaw and three others hold the SI-C booster during static firing. Each jaw exerts 3 million pounds of force. The vector is parallel to datum B passing through the center of the 9.704 inch radius.

The jaw pivots about the 11.000 inch diameter hole and is actuated by a hydraulic ram attached to the 6.750 inch diameter hole. One of the problems of installing this jaw was to establish a reference system to be used to set the actuator length. Thus the force would be in the right direction when the actuator reached its stop. At the time the reference system was put on it wasn't known whether horizontal or vertical lines would be used. This was due to the other construction in progress in the area. As a precautionary measure both horizontal and vertical targets were layed out. These were located from datum plane A.

In order to make the layout, the part was set on jacks and leveled using a sight level. To establish datum, plane A required the fabrication of two plates. One plate, 19.408 inches in diameter, had a boss faced on one side 12.408 inches in diameter. When this plate was nested against the 9.704 inch diameter radius, the edge of the boss established the 6.204 inch dimension. The second plate was turned slip fit for the 11.000 inch diameter hole with a target in the center. Then with these two plates in position a telescope bucked in on the center of the hole and the edge of the plate establishes datum plane A.

A 1 second theodolite was used to establish datum plane A. To establish datum plane B, a second theodolite was set approximately 90 degrees from A and pointed on the target in the plate. Horizontal scales of both theodolites were then set to zero. Next the two telescopes were pointed at each other, collimated, and their horizontal scales read. These readings were then converted to the angle turned and the angles added. If the total was not 90 degrees, theodolite B. was reset to zero and turned the compliment of the scale reading of theodolite A. It then pointed to one side of the target so it was moved laterally to point on the target. This process was repeated until theodolite B was 90 degrees from datum plane A and pointed on the target, thus establishing datum plane B.

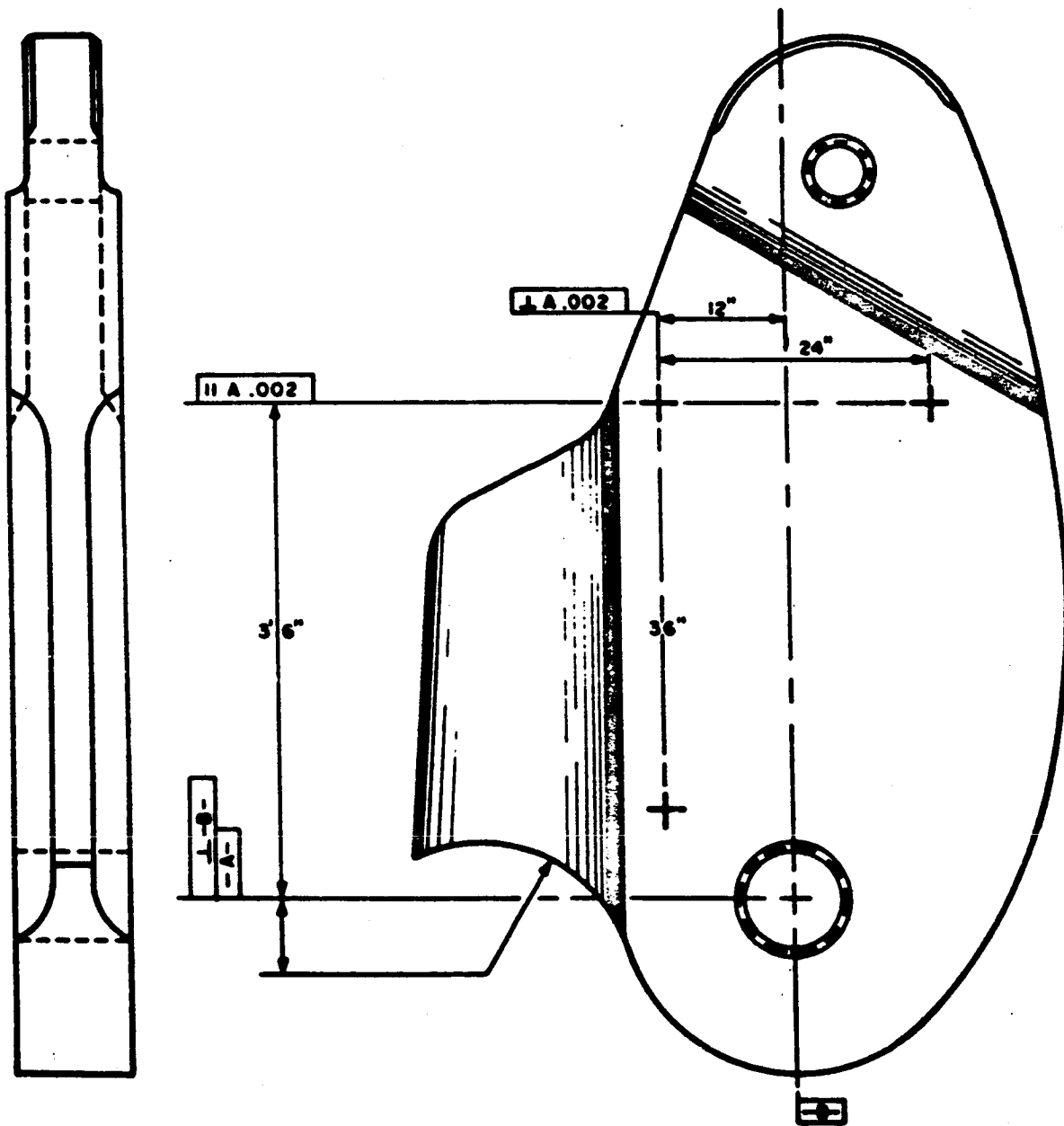


Figure 6-1. S-1C Test Stand Hold Down Jaw

After datum plane B was established, two 20-inch whyteface scales were set perpendicular to B, aligned at the 20-inch graduation. Theodolite B was then moved and bucked in on the 8-inch graduation. The 3.5-foot and 30-foot dimensions were measured with a tape from datum A and the targets aligned with theodolite B. The reference system parallel to datum A was put on in a similar manner.

In theory this method seems good but the accuracy of establishing such a right angle should be questioned. The following test was conducted at the MSFC Calibration Laboratory to determine the accuracy of 1 second theodolites. Two collimators were set on a ridged support perpendicular to each other and at the same elevation. Temperature was maintained within 1°F. The right angle was established using a jig transit which had previously been adjusted. At infinity the line of sight of the transit was perpendicular to the horizontal axis within less than 1 second. The axle mirror was perpendicular to the horizontal axis within less than 1 second. This transit was collimated with one collimator through a calibrated wedge, and the other collimator was auto-collimated with the axle mirror. Thus the angle between the collimators was within 2 seconds of 90 degrees. Infinity focus of the collimators had been verified as described in Section III.

Theodolites tested were a Hilger Watts number two ST 200-3, Wild T-2, and K & E 2E. Instruments were placed on the center post and collimated with left collimator. After setting horizontal scales, telescopes were turned 90 degrees as measured with the scale. Then the right collimator was sighted. If reticles didn't coincide they were brought to coincidence using the wedge. Angular deviation between the scale readings and the setup were thus measured with the wedge. This wedge had previously been calibrated and was accurate to 0.1 second. Three readings were taken for each section of the scale. Average readings will be used for comparison. Table 6-1 was made from these readings. All values are in seconds.

From this data it looks as though an angle can be turned with a 1 second theodolite with an accuracy better than 6 seconds. However, if the telescope is transited more than about 4 degrees above or below the elevation axis another factor enters in. Any nonperpendicularity between the vertical and horizontal axis changes the plane of sight generated by the theodolite. Angles turned to points on this plane will be less than, greater than, or equal to the scale reading depending on differences in elevation. Vertical to horizontal axis relationship of the instruments tested was not perpendicular by as much as 15 seconds. This is not adjustable.

If the instrument is used in the prescribed manner, the accuracy of turning angle is increased. Horizontal angles should be turned from left to right with the instrument in the normal position. Then the angle should be turned from right to left, resetting zero on the right, with the instrument reversed. The mean of these two readings is more accurate than either reading because errors in instrument geometry are neutralized. Also another segment of the circle is used. Accuracy of 5 seconds can be obtained with this method.

On the hold down jaw two targets were to be positioned so their centers were parallel to datum A within 0.002 inch. Two other targets were to be perpendicular to A within 0.002 inch. As previously explained two theodolites were used. Since the instruments were at the same elevation, the accuracy of establishing 90 degrees would be 12 seconds or better. Exact location was not important so the effect of instrument error would be the sine of 12 seconds 0.0000576, multiplied by 36 inches and multiplied by 24 inches. This would be 0.002 inch in 36 inches, and 0.0015 inch in 24 inches.

The student is expected to perform the alignment as first described. Then in order to compare the relative accuracy of the two methods, perform this alignment using jig transits. Datum A will be established as before, except a jig transit will be used in place of a theodolite. A second transit will be auto collimated with the axle mirror of the first. Next, without disturbing the second transit, collimate the first transit with the second. Then turn the second transit so its axle mirror can be auto collimated with the first transit. Use the second transit to position a third transit perpendicular to the second and pointing on Datum B. Scales can be positioned in line with this third transit to establish the 12 inch dimension as before. The 42 inch and 36 inch dimensions can be established in a similar manner using a tape.

Table 6-1. Theodolite Test Data

K & E 2E

0 to 90°

1.	+2.0	Average
2.	+3.5	2.7
3.	+2.5	

180 to 270°

1.	-1.0	Average
2.	0.0	-0.7
3.	-0.1	

45 to 135°

1.	+3.5	Average
2.	+3.5	3.7
3.	+4.0	

225 to 315°

1.	+1.0	Average
2.	+1.5	0.8
3.	0.0	

90 to 180°

1.	+1.0	Average
2.	+0.5	0.8
3.	+0.8	

270 to 360°

1.	+0.8	Average
2.	-1.5	0
3.	+0.8	

135 to 225°

1.	-2.5	Average
2.	-2.1	2.5
3.	-2.8	

315 to 45°

1.	-0.8	Average
2.	-1.2	-0.7
3.	0.0	

Vertical to Horizontal Axis - 15 seconds

Table 6-1. (Continued)

Wild T-2

0 to 90°

1.	-0.8	Average
2.	-1.1	-1.0
3.	-1.0	

180 to 270°

1.	-0.6	Average
2.	-0.7	-0.4
3.	-0.1	

45 to 135°

1.	+0.1	Average
2.	0	-0.3
3.	-1.0	

225 to 315°

1.	-0.1	Average
2.	-1.1	-0.7
3.	-1.0	

90 to 180°

1.	+1.0	Average
2.	+2.0	1.0
3.	+0.5	

270 to 360°

1.	-0.8	Average
2.	0	-0.3
3.	0	

135 to 225°

1.	+2.0	Average
2.	+1.2	1.7
3.	+1.9	

315 to 45°

1.	+0.8	Average
2.	-0.1	0.6
3.	+1.9	

Vertical to Horizontal Axis - 10 Seconds

Table 6-1. (Concluded)

Hilger Watts

0 to 90°			180 to 270°		
1.	-4.5	Average	1.	+2.5	Average
2.	-5.0	-4.8	2.	+2.8	2.6
3.	-5.0		3.	+2.4	
45 to 135°			225 to 315°		
1.	-1.5	Average	1.	0	Average
2.	-1.0	-1.0	2.	+1.0	0.7
3.	-0.5		3.	+1.0	
90 to 180°			270 to 0°		
1.	-1.8	Average	1.	-4.9	Average
2.	-2.2	-2.1	2.	-5.6	-5.2
3.	-2.4		3.	-5.1	
135 to 225°			315 to 45°		
1.	-3.2	Average	1.	-2.4	Average
2.	-2.9	-3.0	2.	-2.5	-2.3
3.	-3.0		3.	-2.0	

Vertical to Horizontal Axis - 6 Seconds

## SECTION VII. CENTROID DETERMINATION

The use of the geometric thrust vector as a reference line for rocket engine alignment has several advantages over the dynamic thrust vector. One of these being that it is a relatively simple method of aligning engine thrust chamber to gimbal block. It can also be used for positioning engines, or checking engine alignment with respect to vehicle references. It can be determined without firing the engine. The method of determining geometric thrust vector, described here has been used for the Jupiter and Saturn I programs, and with slight modification for Saturn V, SI-C stage.

The geometric thrust vector, for the S-3D Jupiter engine and the H-I Saturn engine, can be defined as a centerline through the centers of the throat and exit areas of the engine. For the F-I engine this has been modified. The center of the injector plate is used in place of the center of the throat area.

The equipment described here was used for the S-3D and H-I engines. However, similar equipment could be designed for other applications. The method of centroid calculations will apply to any similar problem where it is necessary to determine centroid of area without determining area.

The S-3D Engine Thrust Alignment Fixture (Figures 7-1 and 7-2) is an adjustable integrating fixture, designed to accurately establish the geometric thrust vector as defined by the centroid of the throat and exit areas. Preliminary investigations revealed that the centroid could best be established by taking readings of the throat and exit radii at 15 degree intervals. These readings were taken with dial indicators mounted on arms affixed to a revolving target tube. The readings were used to calculate the centroid of the throat and exit area, and the calculated correction applied from the position of the target tube from which the indicator readings were taken. To accomplish this, the target tube was made adjustable at each end and the dial indicators were used to control the required movement of the target tube to the centroid of the area. To minimize the correction, the target tube was first centered at the throat and the exit on two diameters 90 degrees apart; the 15 degree readings are then taken. The diameters are also parallel to the fin planes.

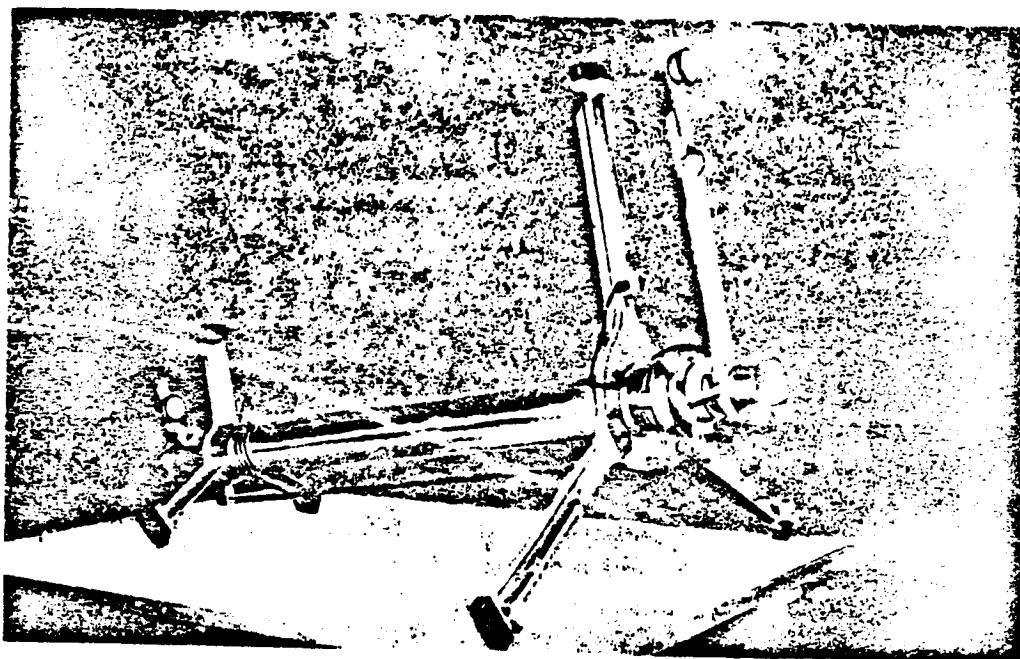


Figure 7-1. Aft View of Thrust Alignment Fixture GM 543987

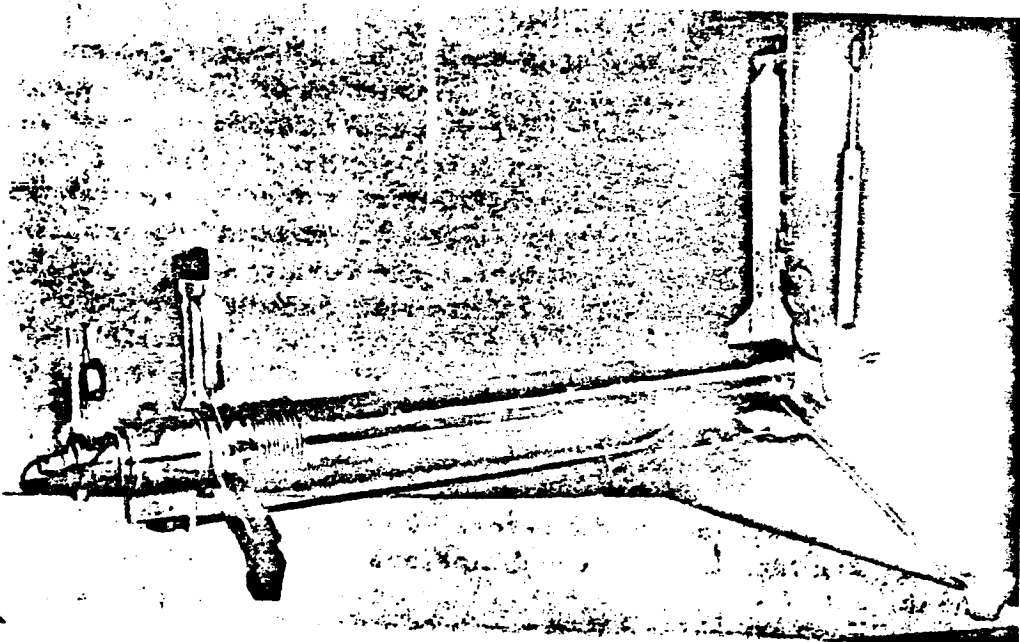


Figure 7-2. Forward View of Thrust Alignment Fixture GM 543987

A typical set of indicator readings taken on this alignment fixture are shown in Table 7-1.

The area based on the average radius of 22.675 is 1605.4550. This area is used to determine the centroid by the method of calculation shown in Table 7-2. A more exact area is calculated for each missile by the Computation Laboratory and given on an alignment drawing. The chamber tubes at which the preliminary readings shown in Table 7-1 were taken are marked for future reference. In this way the thrust alignment fixture can be reinstalled and repositioned after static firing and any change in chamber contour can be determined.

A typical plot of chamber contour change due to static firing is shown in Figure 7-3. The shift in the centroid of the area is also shown. Since the indicator readings are taken at the smallest part of the throat and at the exit diameter, the readings taken for the centroid determinations can also be used for finding the areas of the throat and exit. The computation of the throat and exit areas is made by the Computation Laboratory since these areas are not needed for the alignment procedure.

The thrust alignment fixture shown in Figures 7-4 and 7-5 may be used with the engine in any position since it is self contained and held in position by a retaining ring which fits in the aft stiffener band of the engine chamber. When the fixture is used in conjunction with the S-3 engine alignment stand, the displacement of the throat and exit target from a reference line through the geometric center of the three mount pads, and perpendicular to them can be read directly by use of the optical micrometer built into the alignment telescope. Angularity of the exit cone can be calculated from the displacement of the targets or it can be adjusted out by changing the actuator center to center distance while viewing one target and then the other until the two fall on the same vertical line. Lateral displacement of the thrust vector at the gimbal plane can be measured directly after adjusting out angularity.

The thrust alignment fixture is also used when checking engine alignment to the missile centerline. In this application the displacement of the throat and exit target is read from the missile centerline and lateral displacement of the thrust vector at the gimbal plane and angularity of the exit cone centerline is calculated. No adjustment of the actuators or of the chamber at the gimbal should be required at this time; however, it is possible to realign a chamber to the engine gimbal center and the missile centerline after the engine has been mounted and the missile is in the horizontal position.

Table 7-1.

## Original Data For Calculation of Centroid and Area

Position			Indicator	Delta	Exit
Fin	Radius	Angle	Reading	Radius	Radius
I	R1	0°	.784	.060	22.666
	R2	15°	.746	.022	22.628
	R3	30°	.724	.000	22.606*
	R4	45°	.760	.036	22.642
	R5	60°	.814	.090	22.696
	R6	75°	.830	.106	22.712
II	R7	90°	.830	.106	22.712
	R8	105°	.831	.107	22.713
	R9	120°	.774	.050	22.656
	R10	135°	.747	.023	22.629
	R11	150°	.727	.003	22.609
	R12	165°	.751	.027	22.633
III	R'1	180°	.784	.060	22.666
	R'2	195°	.790	.066	22.672
	R'3	210°	.786	.062	22.668
	R'4	225°	.785	.061	22.667
	R'5	240°	.803	.079	22.685
	R'6	255°	.813	.089	22.695
IV	R'7	270°	.828	.104	22.710
	R'8	285°	.841	.117	22.723
	R'9	300°	.841	.117	22.723
	R'10	315°	.834	.110	22.716
	R'11	330°	.803	.079	22.685
	R'12	345°	.806	.082	22.688

\* Minimum radius

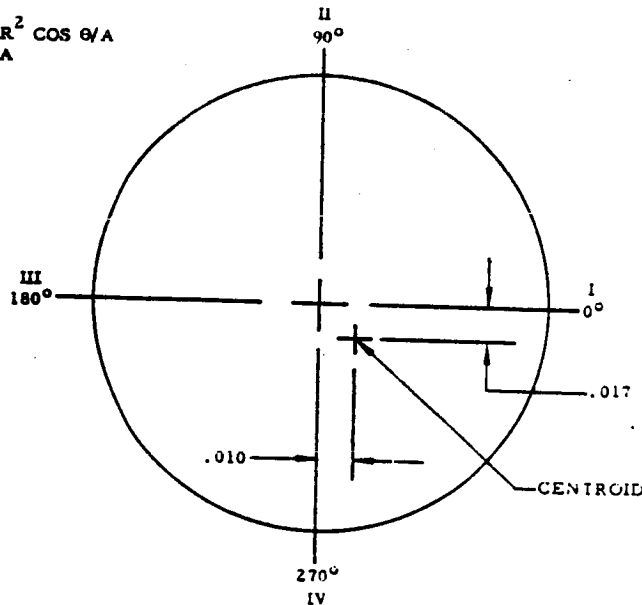
Readings taken on alignment  
fixture GM 543987

Average Radius = 22.675

Table 7-2. Calculation of Centroid of Exit Area

FIN	ANGLE	ΔR	ΔR <sup>2</sup>	C SIN θ	C COS θ	CΔR SIN θ	CΔR <sup>2</sup> SIN θ	CΔR COS θ	CΔR <sup>2</sup> COS θ
I	0°	.060	.0036	0	5.0000	0	0	.3000	.0180
	15°	.022	.0005	5.1764	19.3184	.1139	.0026	.4250	.0097
	30°	.000	.0000	5.0000	8.6603	0	0	0	0
	45°	.036	.0013	14.1422	14.1422	.5091	.0184	.5091	.0184
	60°	.090	.0081	8.6603	5.0000	.7794	.0702	.4500	.0405
	75°	.106	.0112	19.3184	5.1764	2.0478	.2164	.5487	.0580
II	90°	.106	.0112	10.0000	0	1.0600	.1120	0	0
	105°	.107	.0115	19.3184	-5.1764	2.0671	.2222	-.5519	-.0544
	120°	.050	.0025	8.6603	-5.0000	.4330	.0217	-.2500	-.0125
	135°	.023	.0005	14.1422	-14.1422	.3253	.0071	-.3253	-.0071
	150°	.003	.0000	5.0000	-8.6603	.0150	0	-.0260	0
	165°	.027	.0007	5.1764	-19.3184	.1398	.0036	-.5216	-.0135
III	180°	.060	.0036	0	10.0000	0	0	0	0
	195°	.066	.0044	-5.1764	-19.3184	-.3416	-.0228	-1.2750	-.0450
	210°	.062	.0038	-5.0000	8.6603	-.3100	-.0190	-.5369	-.0329
	225°	.061	.0037	-14.1422	-14.1422	-.8627	-.0523	-.8627	-.0523
	240°	.079	.0062	-8.6603	-5.0000	-.6842	-.0537	-.3950	-.0310
	255°	.089	.0079	-19.3184	-5.1764	-1.7193	-.1526	-.4607	-.0409
IV	270°	.104	.0108	-10.0000	0	-1.0400	-.1080	0	0
	285°	.117	.0137	-19.3184	5.1764	-2.2603	-.2647	.6056	.0709
	300°	.117	.0137	-8.6603	5.0000	-1.0133	-.1187	.5850	.0683
	315°	.110	.0121	-14.1422	14.1422	-1.5556	-.1711	1.5560	.1711
	330°	.079	.0062	-5.0000	8.6603	-.3950	-.0310	.6842	.0537
	345°	.082	.0067	-5.1764	19.3184	-.4245	-.0347	1.5841	.1294
	360°	.060	.0036	0	5.0000	0	0	.3000	.0180
Sum of above positive values						+ 7.4904	+ .6742	+7.5477	+ .6562
Sum of above negative values						-10.6065	-1.0286	-5.8001	-.3707
Algebraic sum of above						-3.1161	-.3544	+1.7406	+ .2855
Multiplying by .01745 (rad. per degree)						-.0544	-.0062	+ .0304	+ .0050

$$\begin{aligned} \bar{Y} &= R \min. \sum C \Delta R \text{ SINE } \theta + R \min. \sum C \Delta R^2 \text{ SINE } \theta / A \\ &= (511.0312)(-.0544) + (22.6060)(-.0062) \\ &= -27.8001 - .1402 / A \\ &= \frac{-27.940}{1605.455} = -.017 \text{ in.} \\ \bar{X} &= R \min. \sum C \Delta R \text{ COS } \theta + R \min. \sum C \Delta R^2 \text{ COS } \theta / A \\ &= (511.0312)(.0304) + (22.6060)(.0050) / A \\ &= 15.5353 + .1130 / A \\ &= \frac{15.648}{1605.455} = .010 \text{ in.} \end{aligned}$$



Prepared from data taken on Alignment Fixture GM 543987

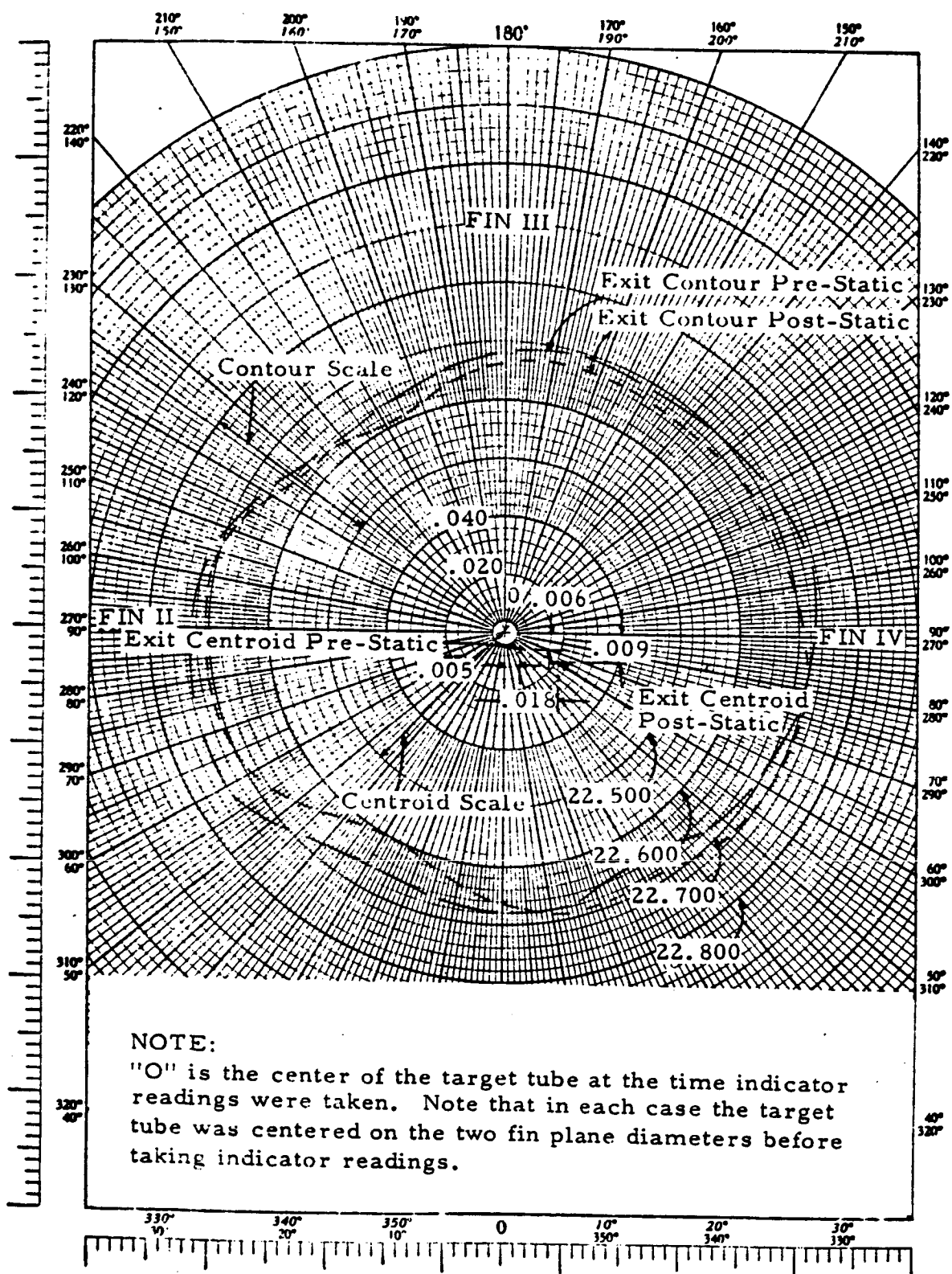


Figure 7-3. Change of Exit Contour and Location of Centroid as the Result of Static Firing

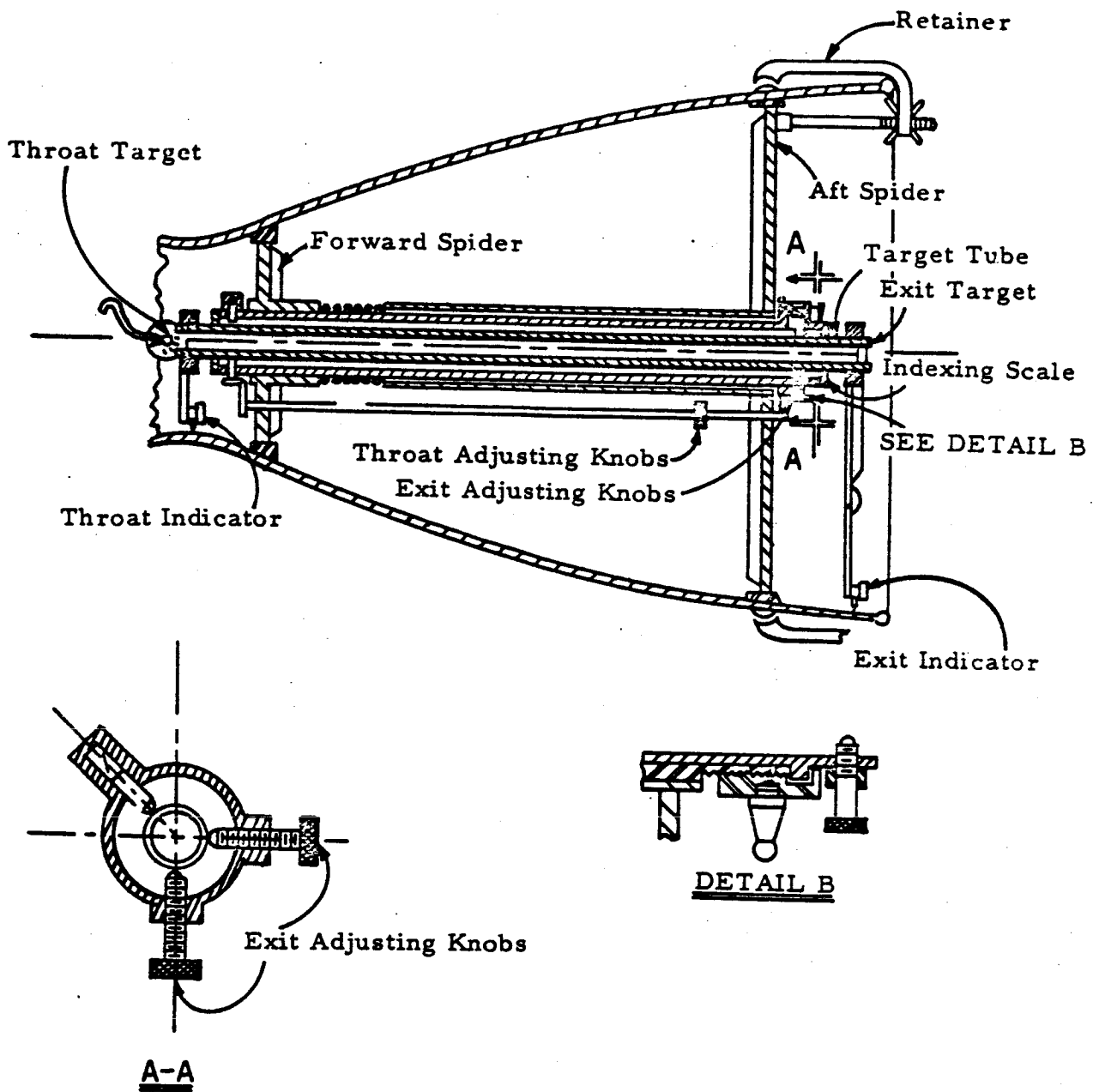


Figure 7-4. S-3D Engine Thrust Alignment  
Fixture GM 543987

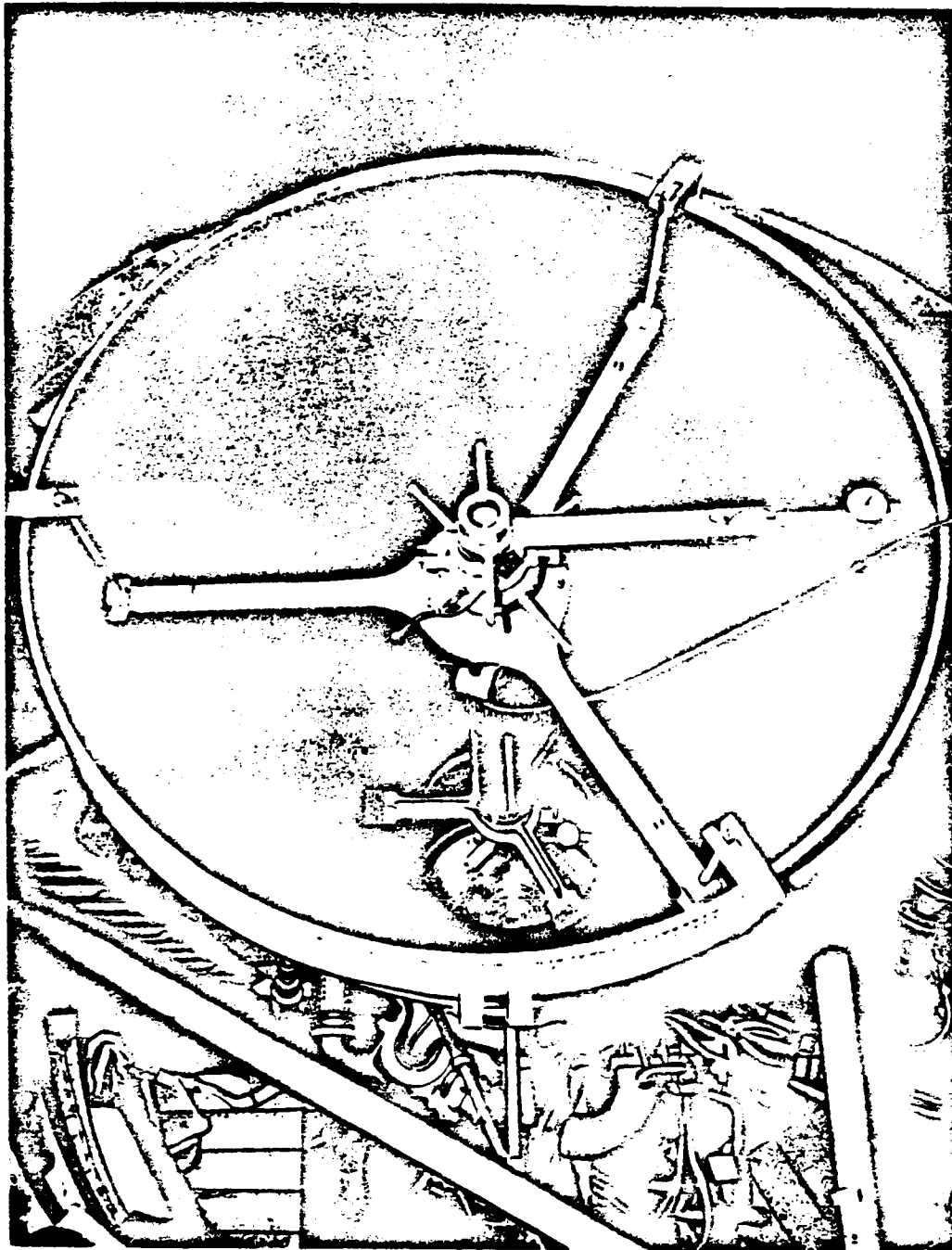


Figure 7-5. Thrust Alignment Fixture GM 543987 Installed in S-3D Engine Thrust Chamber

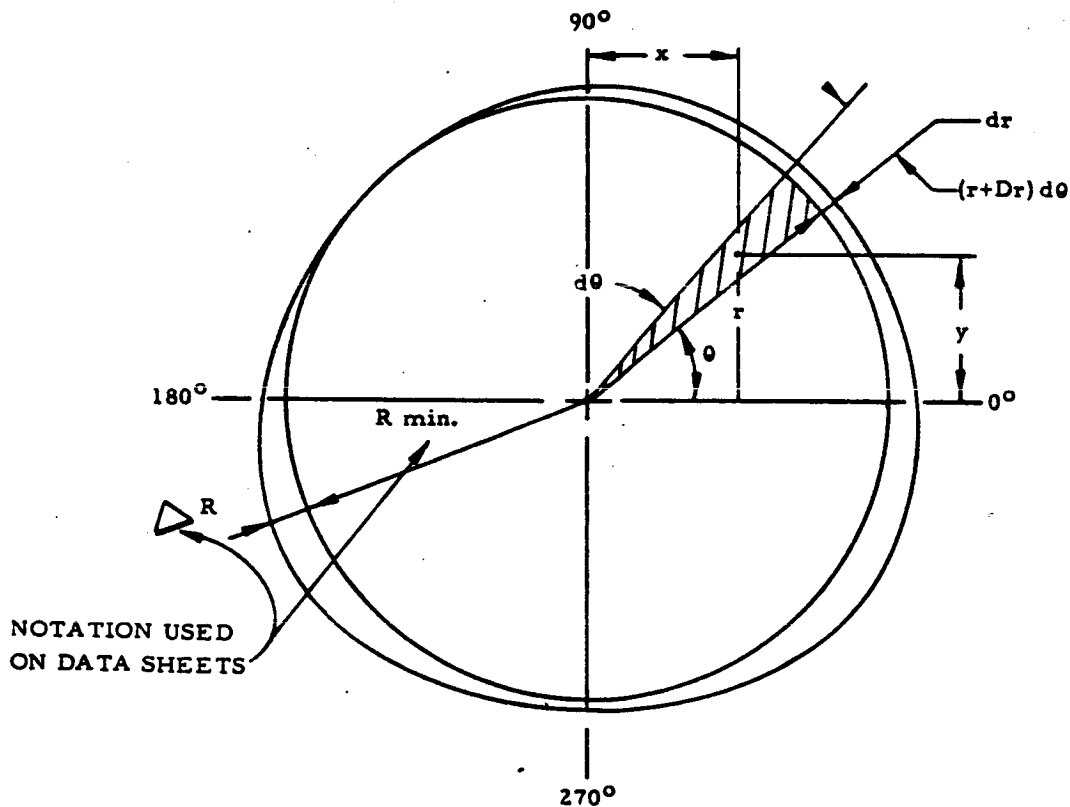
During design of thrust alignment fixture it was felt that sufficient accuracy would be obtained if the centers of twelve diameters were plotted on polar coordinate paper and the average center of the twelve centers determined by algebraic summation. Soon after the thrust alignment fixture was put into use the Test Flight Analysis Section of the Aeroballistics Laboratory made an extensive study of the problem of determining the centroid of an irregular shape object. Their findings indicated that the method presented above was not sufficiently accurate and a new method of computing the centroid was therefore developed. The computation is based on the same dial indicator readings which are taken every 15 degrees. A typical calculation is shown in Table 7-2. The minimum radius value is taken from Table 7-1.

Comparison of the results of the first calculated values with the plotted values showed that the plotted values were one half the calculated value. An investigation was made by the Aeroballistic Laboratory to determine if this would always be true. It was found that the plotted value is not exactly one half the calculated value; however, since this investigation, 95 separate engine alignments have been made. In each case the calculated values were twice the plotted values to within a few thousandths of an inch. Since these 95 engine alignments cover a range of out-of-roundness from approximately zero to three quarters of an inch, it is believed that sufficient accuracy can be obtained by doubling the values obtained by the plotting method.

During the alignment procedure it is often necessary to know the location of the centroid within a short time after the dial indicator readings have been taken. Calculation of the centroid required a considerable amount of time, and errors were always possible before a complete check. For this reason the Computation Laboratory was requested to make the computations, provided the tests were run during regular working hours. In addition the possibility of error was practically eliminated. However, since it was not always possible to perform the tests during regularly scheduled hours the procedure of plotting the centers of the twelve diameters and then determining the average center by algebraic summation is used during the alignment test with a slight modification.

If, instead of plotting the center of each diameter, the difference in indicator readings for each of the twelve diameters is plotted, the algebraic summation of these points does not require doubling. A typical plot using this procedure is shown in Figure 7-6. As a check of the centroid during the alignment procedure, a short calculation is made which is also based on the difference in indicator readings, a typical calculation of which is shown in Table 7-3. Since this procedure does not give an exact value for the centroid, a check is always made by the Computation Laboratory at the first opportunity to verify the results obtained by plotting. As mentioned earlier, the plotted values have been sufficiently accurate for all cases to date. Computations made by the Computation Laboratory are based on the same equations which were used for the original calculations. The deviation of these equations are given below:

#### Derivation of Equations for the Centroid of Area of an Approximate Circle



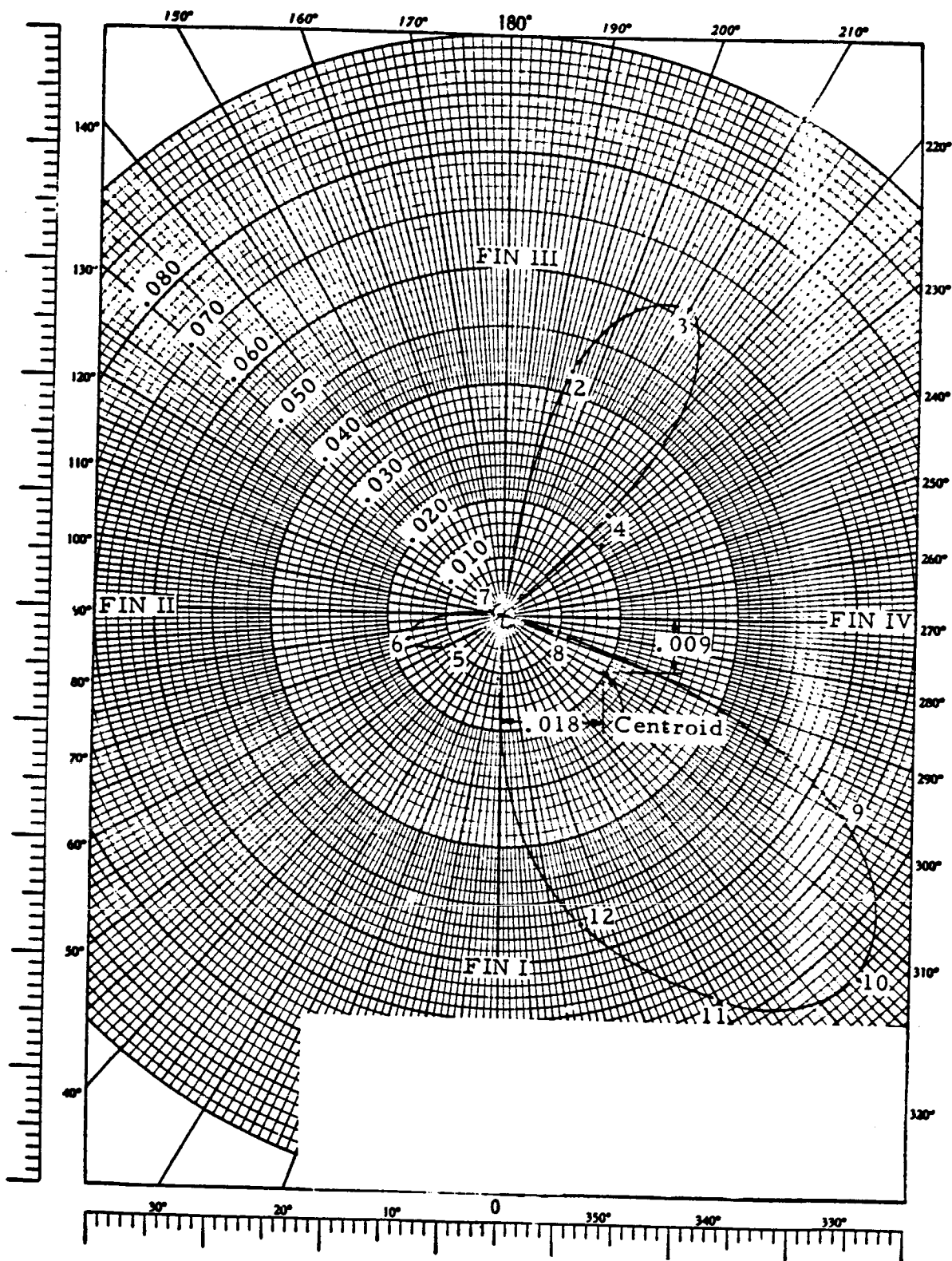


Figure 7-6. Plot Difference in Indicator Readings for Determination of Centroid of Exit Area

Table 7-3. Determination of Centroid by Simplified Calculation

Position			Indicator Reading	Difference in Indicator Readings*	SIN $\theta$	y Component	COS $\theta$	x Component
Fin	Radius	Angle						
I	R1	0°	.784	.000	.0000	.0000	1.000	.0000
	R2	15°	.746	.044	.2588	-.0114	.9659	-.0425
	R3	30°	.724	.062	.5000	-.0310	.8660	-.0537
	R4	45°	.760	.025	.7071	-.0177	.7071	-.0177
	R5	60°	.814	.011	.8660	1.0095	.5000	+.0055
	R6	75°	.830	.017	.9659	+.0164	.2588	+.0044
II	R7	90°	.830	.002	1.0000	+.0020	.0000	.0000
	R8	105°	.831	.010	.9659	-.0097	.2588	+.0026
	R9	120°	.774	.067	.8660	-.0580	.5000	+.0335
	R10	135°	.747	.087	.7071	-.0615	.7071	+.0615
	R11	150°	.727	.076	.5000	-.0380	.8660	+.0658
	R12	165°	.751	.055	.2588	-.0142	.9659	+.0531
III	R'1	180°	.784			-.2136		+.1126
	R'2	195°	.790			$\div 12$		$\div 12$
	R'3	210°	.786			$\bar{y} = -.018$		$\bar{x} = +.009$
	R'4	225°	.785					
	R'5	240°	.803					
	R'6	255°	.813					
IV	R'7	270°	.828					
	R'8	285°	.841					
	R'9	300°	.841					
	R'10	315°	.834					
	R'11	330°	.803					
	R'12	345°	.806					

\* For Each Diameter

### Determination of Y Component of the Centroid

$$y = \frac{2}{3} r \sin \theta \quad dA = \frac{1}{2} r (r d\theta)$$

$$A\bar{y} = \int y dA = \frac{1}{2} r^2 d\theta$$

$$A\bar{y} = \int \frac{2}{3} r \sin \theta dA \quad dA = \frac{(r + dr)^2 d\theta}{2}$$

Substituting  $(r + dr)$  for  $r$  and  $\frac{(r + dr)^2 d\theta}{2}$  for  $dA$

$$\begin{aligned} A\bar{y} &= \int \frac{2}{3} (r + dr) \sin \theta \frac{(r + dr)^2 d\theta}{2} \\ &= \frac{(r + dr)^3 \sin \theta d\theta}{3} \\ &= \frac{(r^3 + 3r^2 dr + 3r dr^2 + dr^3) \sin \theta d\theta}{3} \\ &= \frac{r^3}{3} \int_0^{360} \sin \theta d\theta + r^2 \int_0^{360} dr \sin \theta d\theta \\ &+ r \int_0^{360} dr^2 \sin \theta d\theta + \frac{dr^3}{3} \int_0^{360} \sin \theta d\theta \\ \bar{y} &= \frac{r^2 \int_0^{360} dr \sin \theta d\theta + r \int_0^{360} dr^2 \sin \theta d\theta}{A} \quad (1) \end{aligned}$$

$$* \int_0^{360} \sin \theta d\theta = -\cos \theta \Big|_0^{360} = -(+1) + (+1) = 0$$

### Determination of X Component of the Centroid

$$x = \frac{2}{3} r \cos \theta$$

$$A\bar{x} = \int x \, dA$$

$$A\bar{x} = \int \frac{2}{3} r \cos \theta \, dA$$

Substituting  $(r + dr)$  for  $r$  and  $\frac{(r + dr)^2 \, d\theta}{2}$  for  $dA$

$$A\bar{x} = \int \frac{2}{3} (r + dr) \cos \theta \frac{(r + dr)^2 \, d\theta}{2}$$

$$= \int \frac{(r + dr)^3 \cos \theta \, d\theta}{3}$$

$$= \int \frac{(r^3 + 3r^2 \, dr + 3r \, dr^2 + dr^3) \cos \theta \, d\theta}{3}$$

$$= \frac{r^3}{3} \int_0^{360} \cos \theta \, d\theta + r^2 \int_0^{360} dr \cos \theta \, d\theta$$

$$+ r \int_0^{360} dr^2 \cos \theta \, d\theta + \frac{dr^3}{3} \int_0^{360} \cos \theta \, d\theta^*$$

$$x = \frac{r^2 \int_0^{360} dr \cos \theta \, d\theta + r \int_0^{360} dr^2 \cos \theta \, d\theta}{A} \quad (2)$$

$$* \int_0^{360} \cos \theta \, d\theta = [\sin \theta]_0^{360} = 0$$

Since a true equation cannot be written for the contour of the engine,  $d\theta$  is taken to be  $15^\circ$  and Simpson's Rule is applied.

Simpson's Rule:

$$\frac{h}{3} \left[ (Y_0 + 4Y_1 + Y_2) + (Y_2 + 4Y_3 + Y_4) + (Y_4 + 4Y_5 + Y_6) \dots \right]$$

in this case  $h = 15$  and we have

$$5Y_0 + 20Y_1 + 5Y_2 + 5Y_2 + 20Y_3 + 5Y_4 + 5Y_4 + 20Y_5 + 5Y_6 \dots =$$

$$5Y_0 + 20Y_1 + 10Y_2 + 20Y_3 + 10Y_4 + 20Y_5 \dots$$

Substituting  $R \min.$  for  $r$  and  $\Delta R$  for  $dr$  in (1) and (2) above and applying Simpson's Rule

$$\bar{y} = \frac{R \min.^2 \sum_0^{360} C \Delta R \sin \theta + R \min. \sum_0^{360} C \Delta R^2 \sin \theta}{A}$$

$$\bar{x} = \frac{R \min.^2 \sum_0^{360} C \Delta R \cos \theta + R \min. \sum_0^{360} C \Delta R^2 \cos \theta}{A}$$

By plotting the delta radii for each quadrant, using data from Table 7-1, an approximation of the area outside the minimum radius can be determined for each quadrant. This area is the average of the delta radii, multiplied by pi over two and the average radius (Figure 7-7). Thus the delta area for the first quadrant is 3.348 square inches. The second quadrant is 3.028 square inches. The third quadrant is 4.131 square inches. The fourth quadrant is 5.343 square inches.

The center of area about the 0 to 180° axis is found by adding the first two quadrants and subtracting this from the sum of the other two. This difference is then divided by pi r. One half of the quotient is the distance from the 0 to 180° axis to the Y coordinate of the centroid. The centroid about the 90 to 270° axis is found in the same way (Figure 7-7). By this method the centroid is found to be 0.011 inch toward 0 degrees, and 0.022 inch toward 270 degrees. By the method of plotting difference in radius the centroid is 0.010 toward 0 degrees, and 0.017 inch toward 270 degrees (Table 7-2).

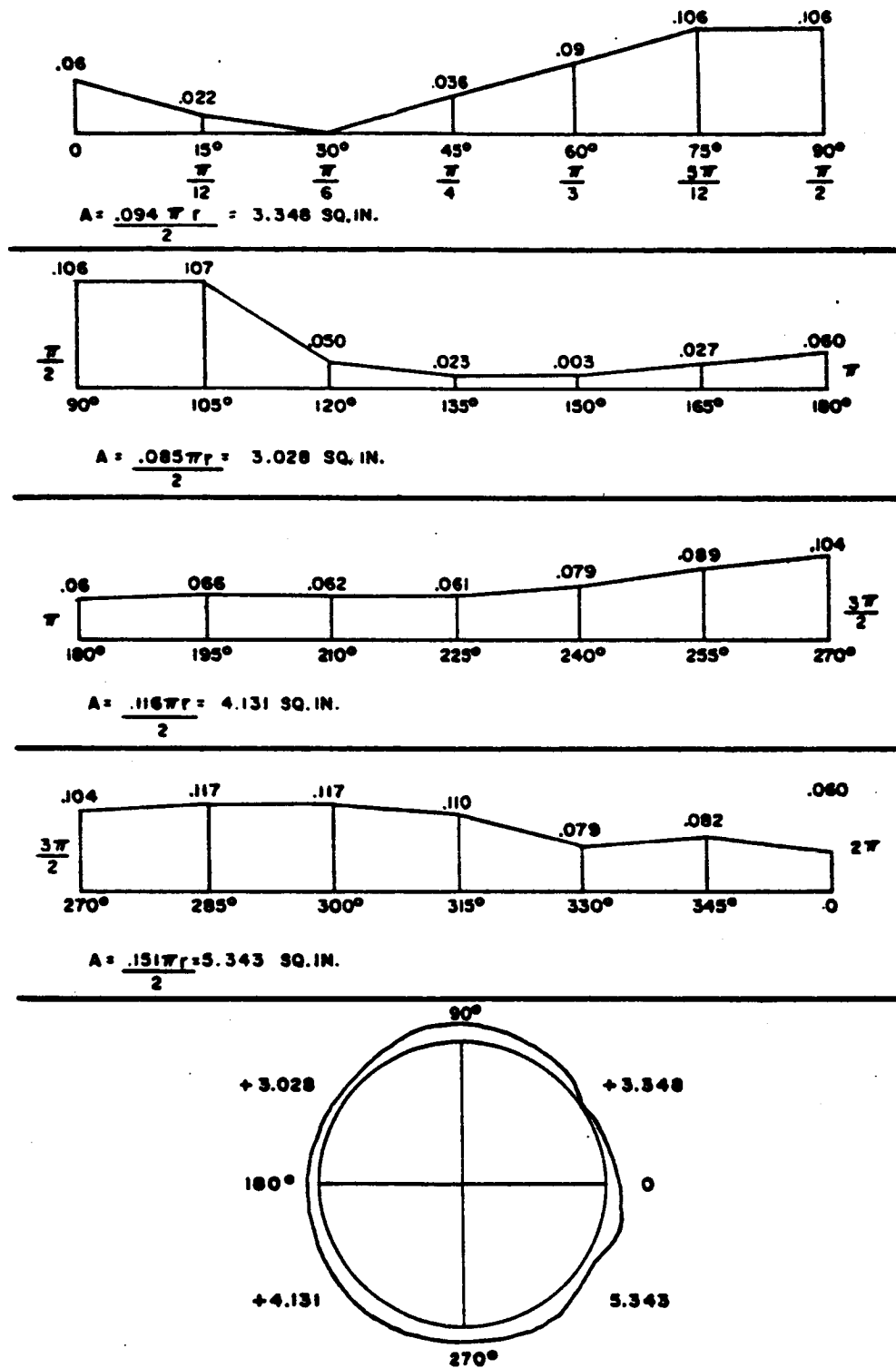


Figure 7-7. Area Outside the Minimum Radius  
7-16

Table 7-4 is a more simplified method of calculating the centroid. Indicator readings are recorded in columns 3 and 5. Their difference is recorded in column 6. From note 3 a plus or minus sign is given for column 6. Column 6 is multiplied by column 7, and their product entered in column 8. Column 6 is also multiplied by column 9 and their product entered in column 10. The algebraic sum of column 8 is averaged. This average is the distance to move the fixture from 0 to 180 degree axis, either toward 90 or 270 degrees, see Notes 1 & 2. The algebraic average of column 10 is the distance to move toward 0 or 270 degrees.

### Table 7-1. Radius and Centroid Data Sheet

Vehicle	R. E. No.		Chamber No.		Date					
Exit										
Position	3	4	5	6	7	8	9	10	11	12
1	2	Ind	Ind	Diff	0-180°	Dist	Axis	Dist	0-180°	180-360°
Fin	Ang	Rdg	Rdg		Factor	From	Factor	From		
0-180°	0°	180°			0		-1.0000			
	15°	195°			-.2588		-.9659			
	30°	210°			-.5000		-.8660			
	45°	225°			-.7071		-.7071			
	60°	240°			-.8660		-.5000			
	75°	255°			-.9659		-.2588			
90-270°	90°	270°			-1.0000		0			
	105°	285°			-.9659		+.2588			
	120°	300°			-.8660		+.5000			
	135°	315°			-.7071		+.7071			
	150°	330°			-.5000		+.8660			
	165°	345°			-.2588		+.9659			
Min Rdg		Algebraic Sum								
		<div style="display: flex; justify-content: space-between;"> <span>Avg <u>12</u></span> <span>Avg <u>12</u></span> </div> <div style="display: flex; justify-content: space-between;"> <span>Min Rdg <u>21.882</u></span> </div>								
Throat										
0-180°	0°	180°			0		-1.0000			
	15°	195°			-.2588		-.9659			
	30°	210°			-.5000		-.8660			
	45°	225°			-.7071		-.7071			
	60°	240°			-.8660		-.5000			
	75°	255°	255		-.9659		-.2588			
90-270°	90°	270°			-1.0000		0			
	105°	285°			-.9659		+.2588			
	120°	300°			-.8660		+.5000			
	135°	315°			-.7071		+.7071			
	150°	330°			-.5000		+.8660			
	165°	345°			-.2588		+.9659			
Min Rdg		Algebraic Sum								
		<div style="display: flex; justify-content: space-between;"> <span>Avg <u>12</u></span> <span>Avg <u>12</u></span> </div> <div style="display: flex; justify-content: space-between;"> <span>Min Rdg <u>7.192</u></span> </div>								

NOTE:

- + Toward 0° & 90°
- Toward 180° & 270°
- If reading in Column 5 is larger than that in Column 3, use a + sign in Column 6. If the reading in Column 5 is smaller than that in Column 3, use a - sign in Column 6.

## SECTION VIII. ALIGNMENT OF JUPITER POWER UNIT

Alignment of the Jupiter power unit was performed in the horizontal position. This was done so that a gravity seeking device could be used to determine the location of the gimbal center. Another advantage of horizontal alignment in this case was that more accurate angular measurements could be taken using the length rather than the diameter as a base line. A disadvantage was that a more elaborate handling fixture was required to compensate for sag (Figure 8-1).

Figure 8-2 delineates alignment requirements. The container unit is 105 inches in diameter and approximately 15 feet long. Before the engine was installed, alignment references were transferred to the outside of the container in the proper relationship to critical structure.

Datum plane T is in the forward end of the container unit. Mounting plates at points A, B, and Fin II contain a socket for locating the spherical head of the thrust frame bolts. The face of these pads is the center of this sphere. Datum line X is the center line of the container and is perpendicular to T. The II-IV fin plane passes through one socket and the container centerline. Fin plane I-III is perpendicular to II-IV and intersects it at the container centerline.

To transfer alignment references to the outside of the container, datum plane T was brought into a vertical position with points A and B in a horizontal plane. The easiest way to set datum plane T vertical was to place a clinometer on one pad and adjust the jacks until that pad was vertical. Then, using the clinometer, measure any deviation of the other two pads. If the other two pads were not vertical the jacks were adjusted until the difference was split out. A and B were leveled with a sight level by placing a Whyte face scale against the thrust frame bolts and rotating the container until A and B were level. Since the centers of the three spherical mounts forms an equilateral triangle, all interior angles are 60 degrees. The intersection of the angle bisectors is the geometrical center, in this case datum X. Thus the distance from line AB to the I-III fin line is 16.696 inches, half the diameter multiplied by the sine of 30 degrees. Using sight levels, targets were placed on the forward and aft end of the container 16.696 inches above line A B, thus establishing the I-III fin plane. Next the container was rotated 90 degrees and points A and B were brought into a vertical line using a transit. Datum plane T was again made vertical using the clinometer. Then, using the sight levels, targets were placed on the forward and aft end to establish the II-IV fin plane at the height

of the third pad. With these targets the center line could be established after the engine was installed.

After the engine is installed, alignment of the engine is checked against Figure 8-2. This includes angular and lateral measurements of the geometric thrust vector and lateral measurements of the gimbal center. The geometric thrust vector must not deviate from line X by more than  $0^{\circ}5'$  and 0.032 inch lateral displacement at the gimbal plane. The gimbal center is located at a true position of 0.125 inch with line X.

Figure 8-3 shows the instrument set up for checking this alignment. The geometric thrust vector was established as previously described. Sight levels were set up at each end, adjusted to the height of a central target. A precision level on the water level fixture (Figure 8-4) was used to control roll. Alignment reference targets on the fin planes were used to level the center line. After the container unit was brought under optical control, readings were taken with the aft sight level of the throat and exit targets and the outside unit of the water level. This data was recorded with the fin reference. See Figures 8-5 through 8-9 for data sheet. This process was repeated four times. Once for each fin position. This data was then used to determine if the engine sagged, the amount of displacement, location of gimbal center, and thrust vector angularity.

The water level fixture consists of two units connected by a hose (Figure 8-10). The C clamp section has two 60 degree centers which fit into machine centers in the ends of the gimbal shafts. The precision level is adjustable so its axis can be made parallel to the centers. On one end is a pointer. Detail two is the water container which screws into the C clamp. It has two adjusting screws which change the area in the water chamber and thus raise or lower the water. The other unit screws onto an N-3 level adapter on an instrument stand. The pointer for this unit has a line 2.000 inches above the point. The point of the pointer on the C clamp is 2.000 inches below the machine centers.

To use the water level fixture, the C clamp is mounted on the engine gimbal shaft. Then the booster is rotated until the gimbal shaft is level as indicated by the level on the clamp. The other unit is attached to an instrument stand and adjusted to the approximate height of the gimbal center. Next the hose is filled with water and attached to both units. Water can be added to the unit on the stand until the chambers of each unit are approximately three fourths full. Using the adjusting

screws on the gimbal unit, the water is raised until it touches the pointer. This has to be done carefully because when the pointer first touches, surface tension will cause the water to raise above the pointer. Next the pointer on the stand unit is screwed down until it touches the water. This also can be affected by surface tension. When both pointers just touch the water the line on the pointer is at the same elevation as the gimbal center. With practice, accuracies of .01 inch can be achieved.

To obtain alignment data a reference target was placed 70 inches above the floor where it could be seen from both ends of the container unit. An N-3 level was placed at each end of the container, in a position where this reference target could be sighted. The forward instrument was used to control elevation only. The aft instrument was used to control elevation and measure elevations at the water level fixture, as well as throat and exit targets of the centroid fixture. Both instruments were aligned with the target with their micrometers set on 0.25 inch.

To bring the container under optical control it was rotated until the gimbal shaft was level. Then with observers on each end the container was raised or lowered until its center line was at the same elevation as the reference target. If any misalignment existed between the fin targets and the gimbal shaft this difference was split out. That is, one target set above the reference line and the other below the reference line by the same amount. Thus the center line would be at the same elevation as the reference.

After optical control was achieved water was added to the water level and both pointers set. Then, using the sight levels, readings were taken of the elevations of fin targets, water level pointer, throat, and exit targets. This data was recorded as the distance from the reference line and the direction, either high or low. The fin position which was down at this time was also logged.

After this process had been repeated with each fin down, the data was put in graph form (Figures 8-11 and 8-12). The difference in elevation of the exit target, throat target, and gimbal center were plotted in the II and IV fin plane, and in the I and III fin plane. The direction of the target from the center line was changed from high or low to reflect which fin it was toward. In the I and III plane with fin I down the exit was 0.151 low. This is shown in figure 8-11 as 0.151 toward fin I. The throat is 0.198 low so it is 0.198 toward fin I.

Then with the container rotated so fin III was down, the exit target was 0.478 low or toward fin III. The throat was 0.159 toward fin III. This difference in position is caused by the engine sagging. That is, its weight causes a deflection of the supporting structure. The location of the throat and exit with the container in the vertical position would be half way between the locations as measured in the two horizontal positions. The measured distance that the exit moved was 0.151 plus 0.478 or 0.629. To calculate the exit location this sag is divided by two and the quotient subtracted from the larger distance. The exit would be 0.164 toward fin III. The throat would be 0.020 toward fin I. The gimbal center is 0.026 toward fin I. The geometric thrust vector passes through the throat and exit.

The intersection of the geometric thrust vector and the gimbal plane is called the pierce point. Once the locations of the throat and exit are known the pierce point location can be calculated. The distance from the throat to the exit is 55.5 inches and from the throat to the gimbal plane is 40.182 inches. The ratio of these distances is 0.724. If the displacement between the exit and throat targets is multiplied by 0.724 this will give the displacement between the throat and pierce point. The pierce point will be located in the same direction from the throat that the throat is from the exit. In figure 8-11 the exit is 0.164 inch toward fin III and the throat 0.020 inch toward fin I. This displacement is 0.184 inch which when multiplied by 0.724 inch gives 0.133 inch. So the pierce point is 0.133 plus 0.020 or 0.153 inch toward fin I.

The pierce point location can also be calculated by similar triangles.

Data reduction for the II and IV fin plane is accomplished in the same way. Then the data from the I and III and II and IV planes is put into rectangular coordinates (Figure 8-13). The gimbal center tolerance zone is a circle 0.125 inch diameter with its center at the container center line. The pierce point tolerance zone is 0.064 in diameter with its center at the gimbal center. In this example the pierce point is out of tolerance. To determine the angle of the geometric thrust vector and container center line the difference between the resultant displacements at the throat and exit is divided by 55.5. The quotient is the sine of the angle. The angle is approximately  $0^{\circ} 8'$ , also out of tolerance.

This angle can be corrected by changing the lengths of the actuators. In changing the angle the pierce point location would also change. The amount and direction of this change can be calculated using the change of actuator length. If this is not enough to correct displacement of the pierce point the chamber can be moved laterally in the fin planes. Whether this would be necessary or not is left to the reader as a problem.

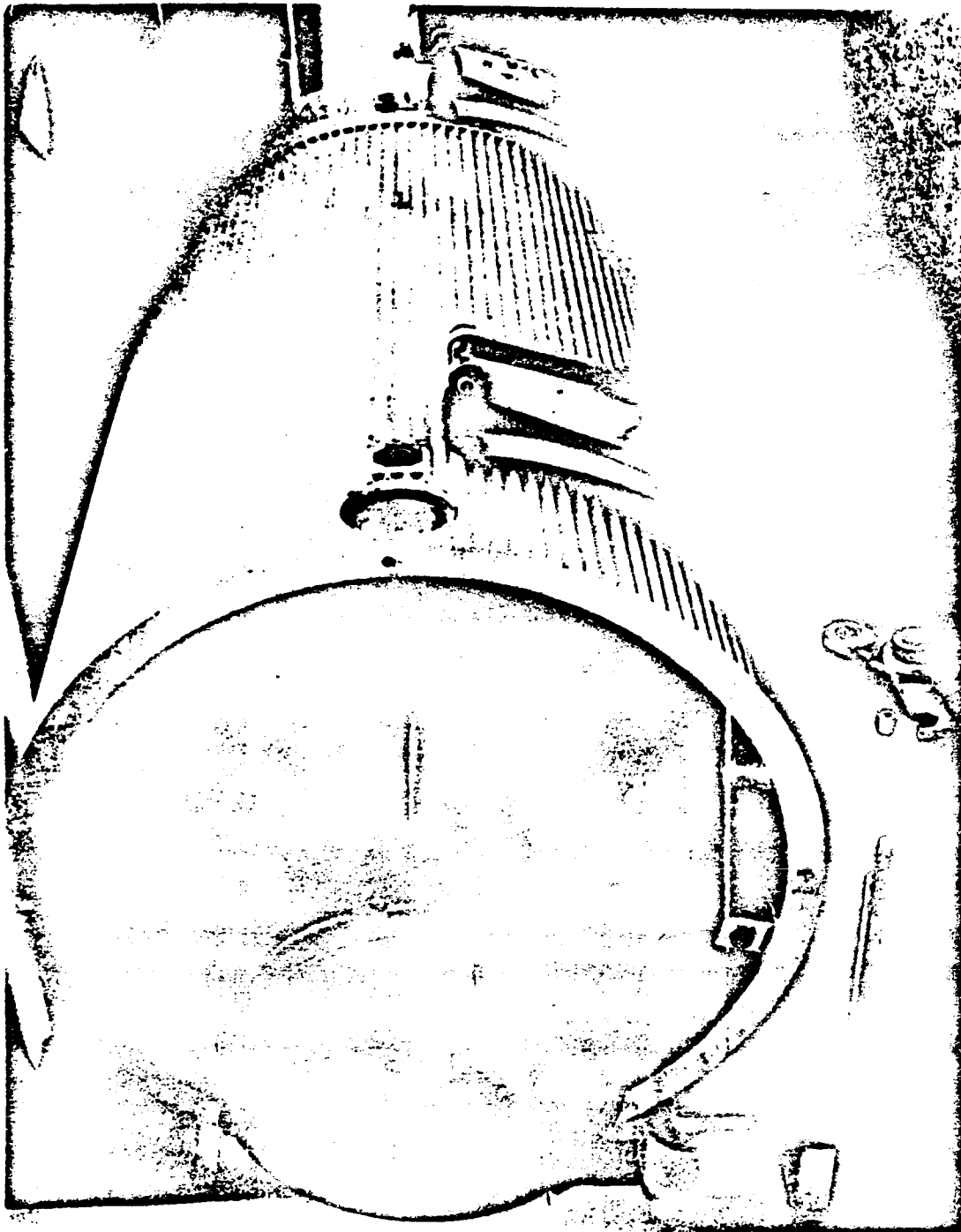


Figure 8-1. Jupiter Power Unit



NOTES:

1. Basic reference plane **-T-** is defined as passing through the center of the spherical radius of connecting thrust frame bolt. See Detail A.
2. Datum line **-X-** is  $\perp$  to basic reference plane **-T-** at the geometric center line of the three engine pads.
3. Plane **-S-** is defined as being parallel to **-T-** and passing through the center of the gimbal cross.
4. The geometric thrust vector **-V-** is defined as passing through the center of the throat and the center of the nozzle exit area.
5. The geometric thrust vector must not deviate from the gimbal cross center by more than .032 inch lateral displacement in plane **-S-** and must not deviate from **-X-** by more than  $0^{\circ}5'$ .

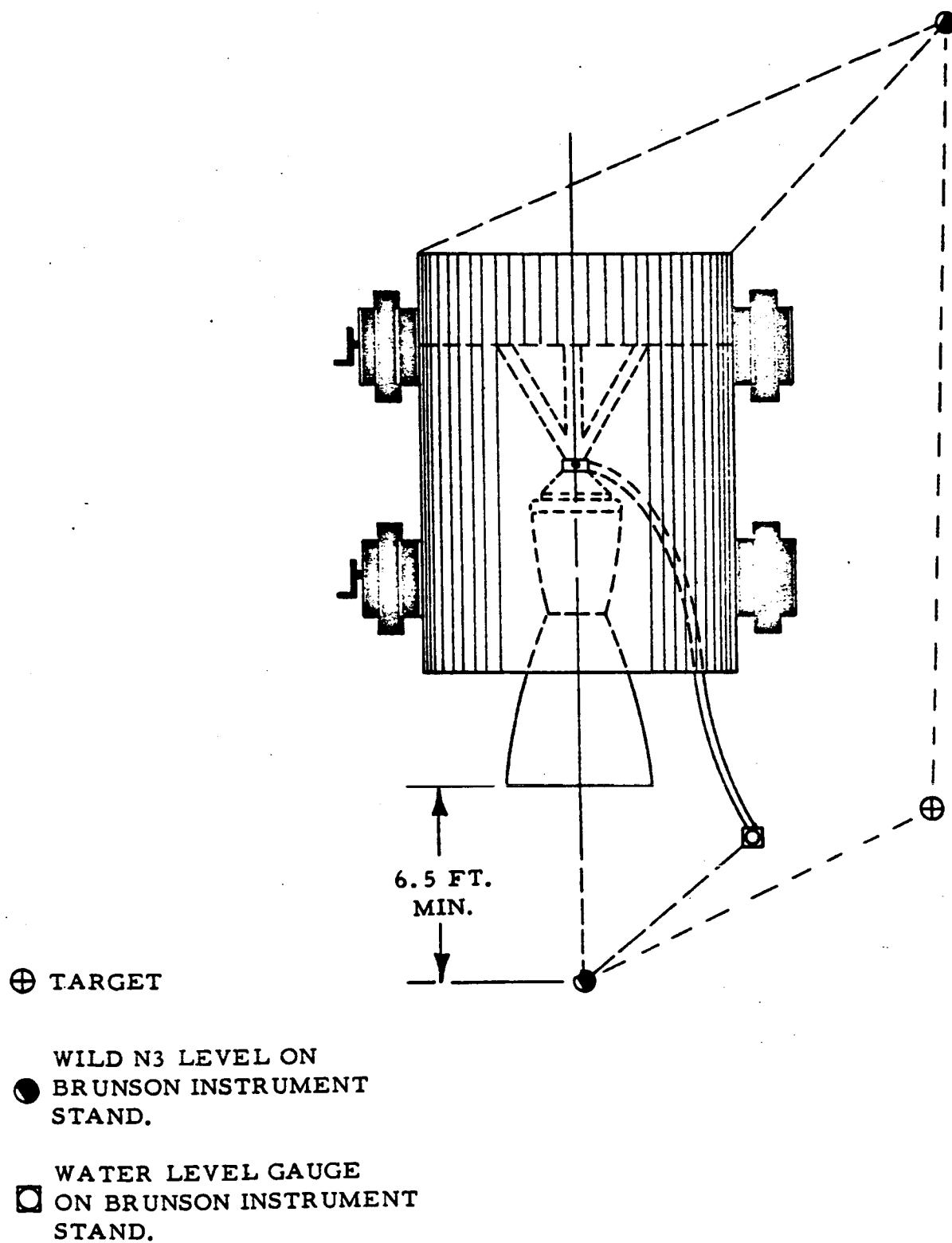


Figure 8-3. Instrument Setup for Rocket Engine Alignment Test to Centerline of Container Unit

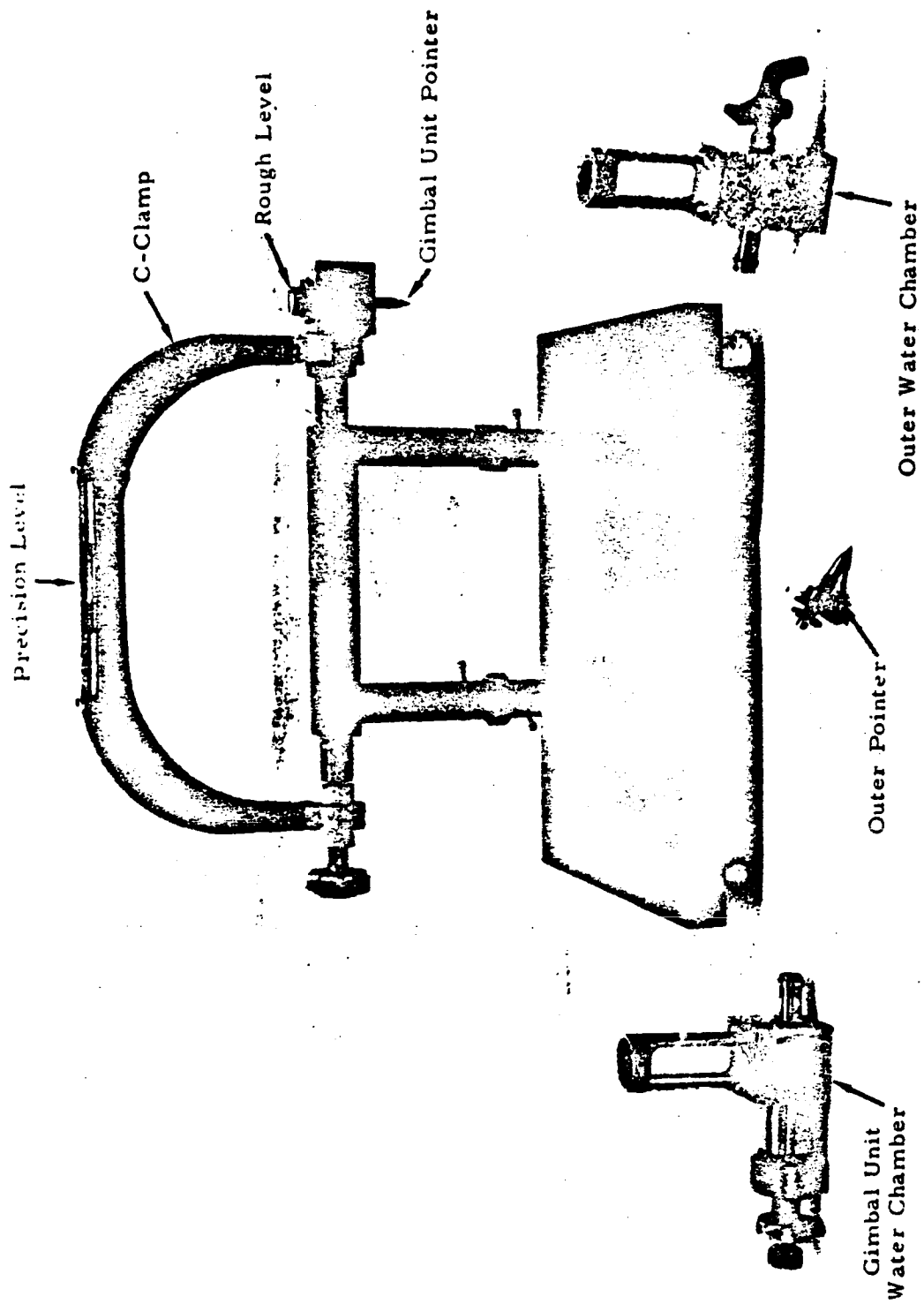


Figure 8-4. Water Level Fixture

MEMO NO: \_\_\_\_\_ RECEIVING ALIGNMENT TEST S-3D ENGINE \_\_\_\_\_ CHAMBER S/N \_\_\_\_\_

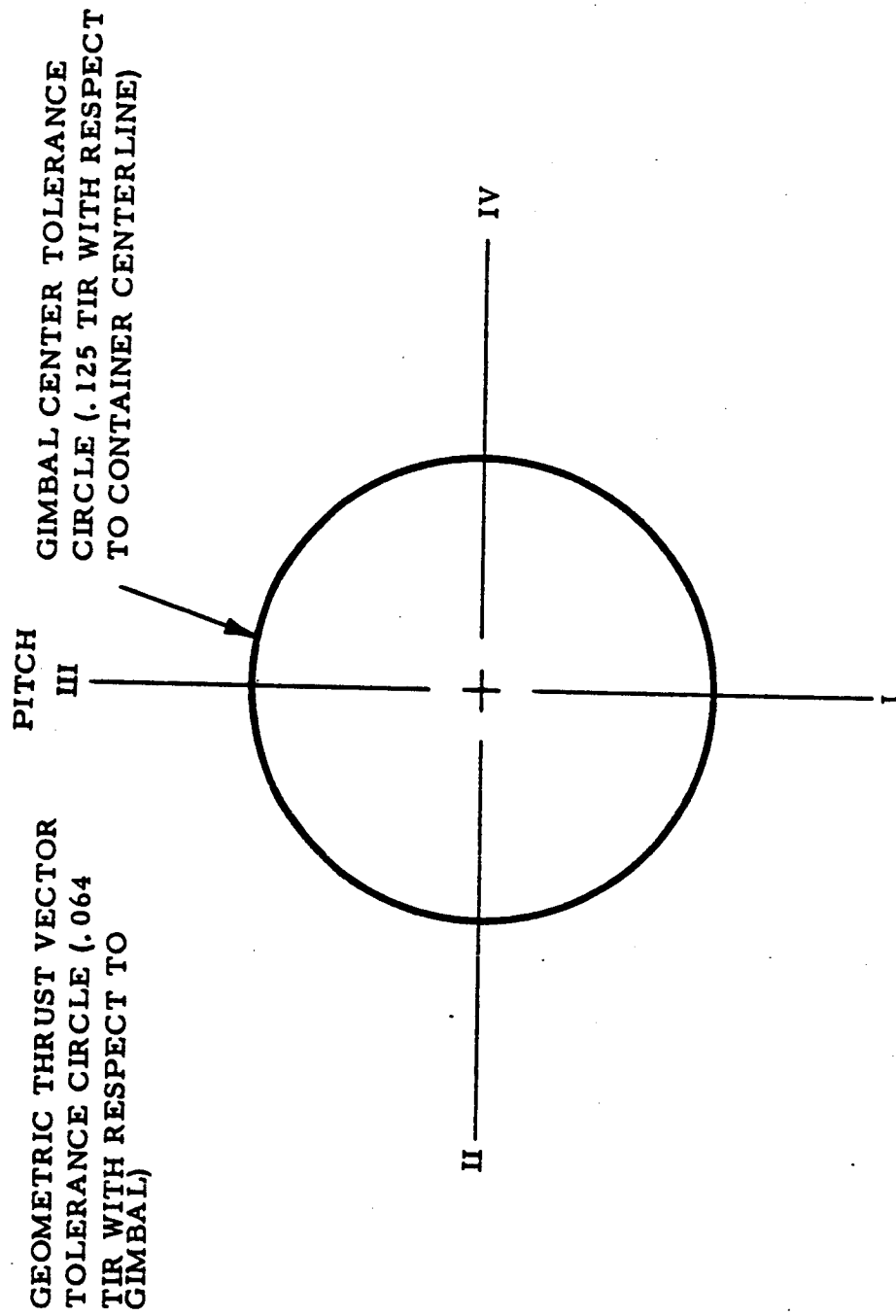


Figure 8-5. Rocket Engine Alignment

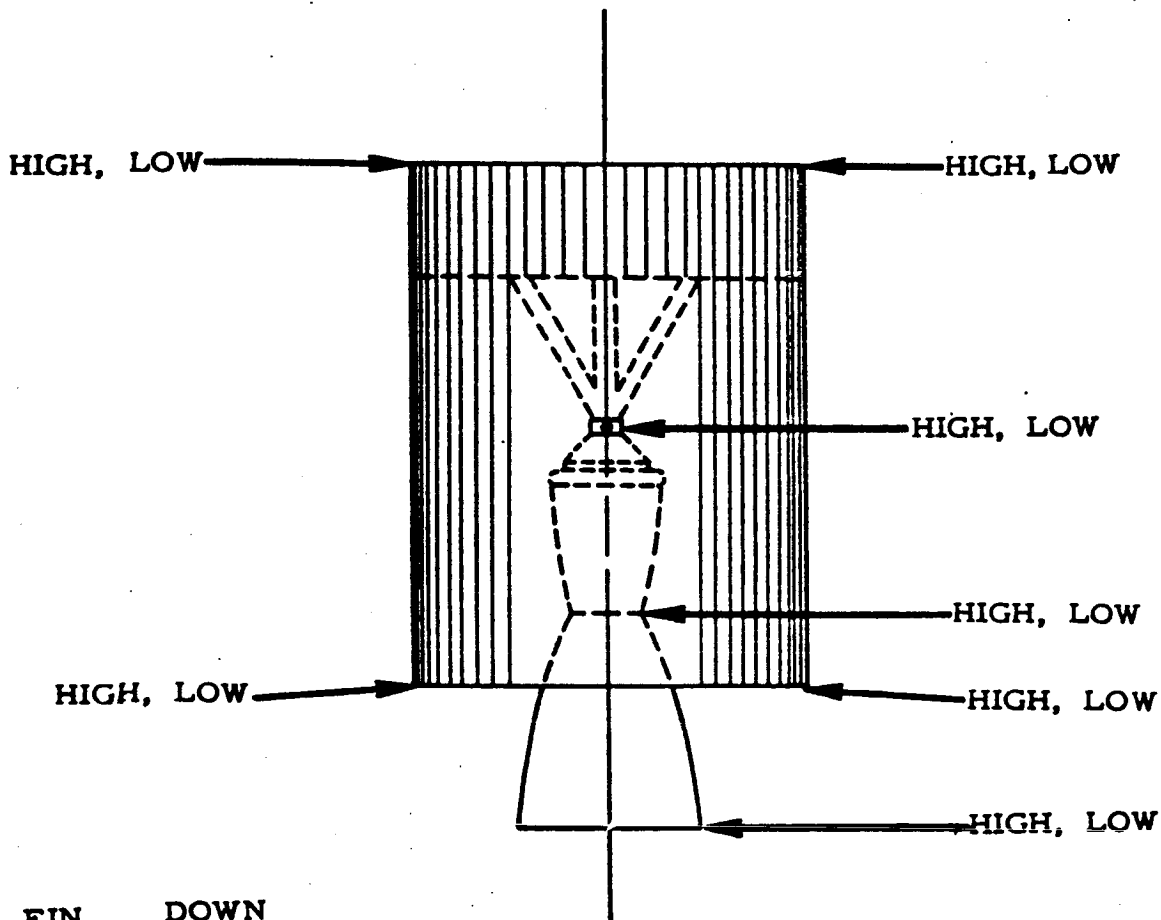
# ALIGNMENT DATA SHEET

R.E. NO. \_\_\_\_\_

DATE: \_\_\_\_\_

CHAMBER NO. \_\_\_\_\_

MISSILE NO. \_\_\_\_\_



FIN \_\_\_\_\_ DOWN  
SHEET \_\_\_\_\_ OF 4

Figure 8-6. Power Unit Alignment

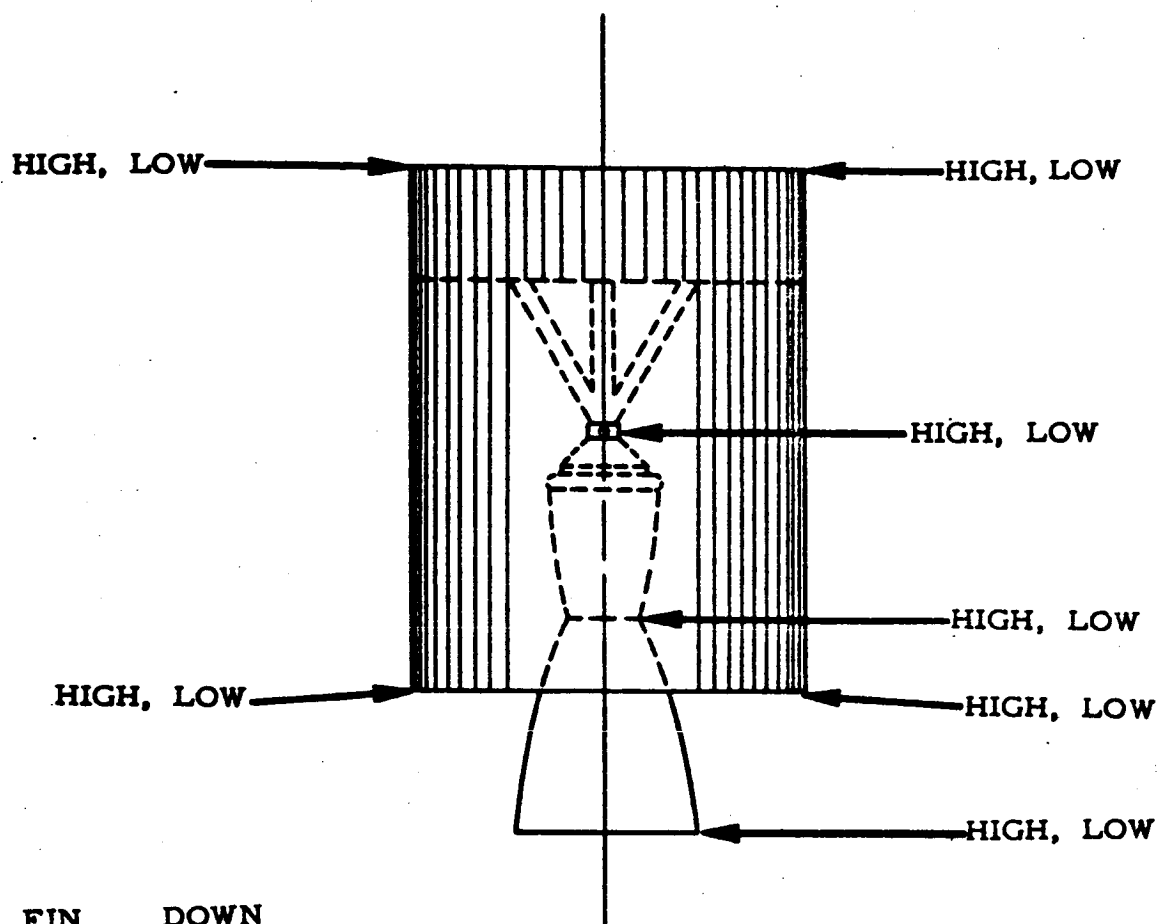
# ALIGNMENT DATA SHEET

R.E. NO. \_\_\_\_\_

DATE: \_\_\_\_\_

CHAMBER NO. \_\_\_\_\_

MISSILE NO. \_\_\_\_\_



FIN \_\_\_\_ DOWN  
SHEET \_\_\_\_ OF 4

Figure 8-7. Power Unit Alignment

8-13

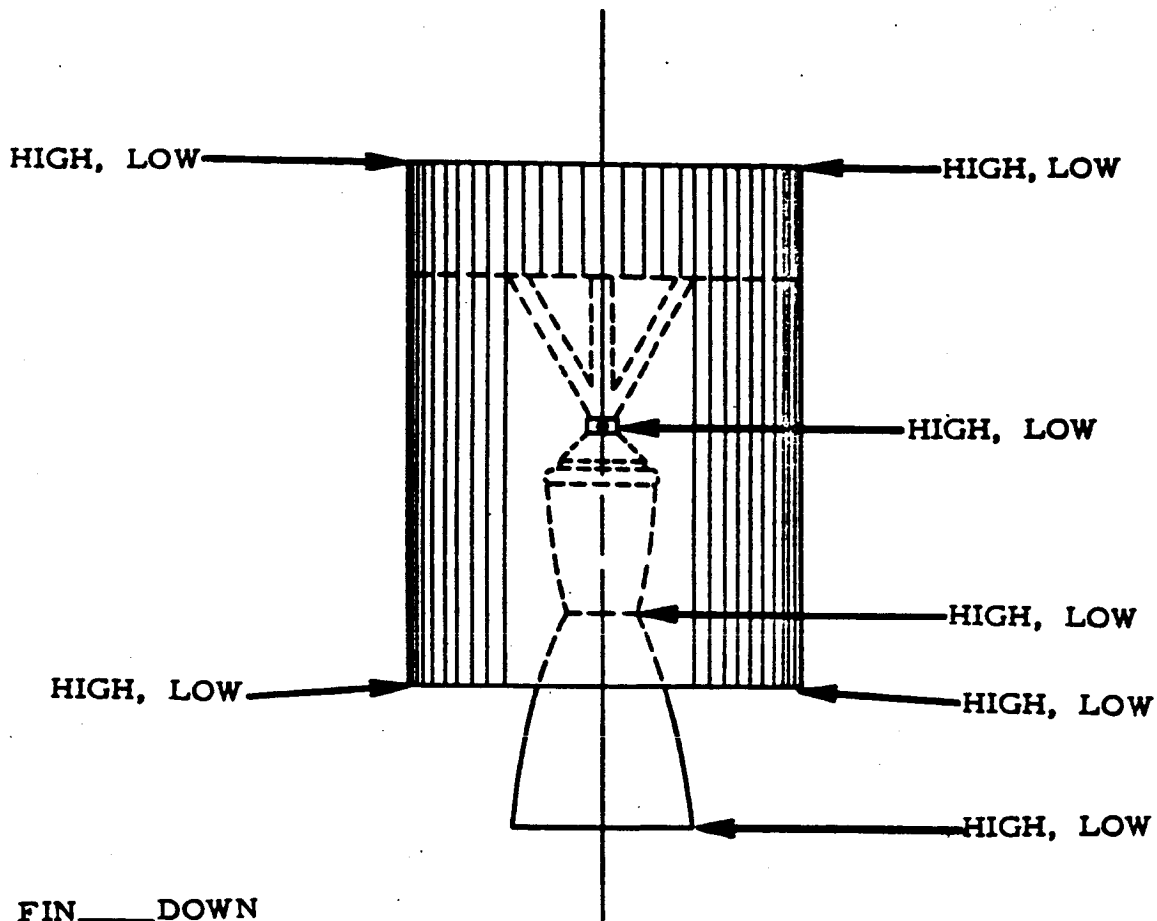
ALIGNMENT DATA SHEET

R.E. NO. \_\_\_\_\_

DATE: \_\_\_\_\_

CHAMBER NO. \_\_\_\_\_

MISSILE NO. \_\_\_\_\_



FIN \_\_\_\_ DOWN  
SHEET \_\_\_\_ OF 4

Figure 8-8. Power Unit Alignment

100

ALIGNMENT DATA SHEET

R.E. NO. \_\_\_\_\_

DATE: \_\_\_\_\_

CHAMBER NO. \_\_\_\_\_

MISSILE NO. \_\_\_\_\_

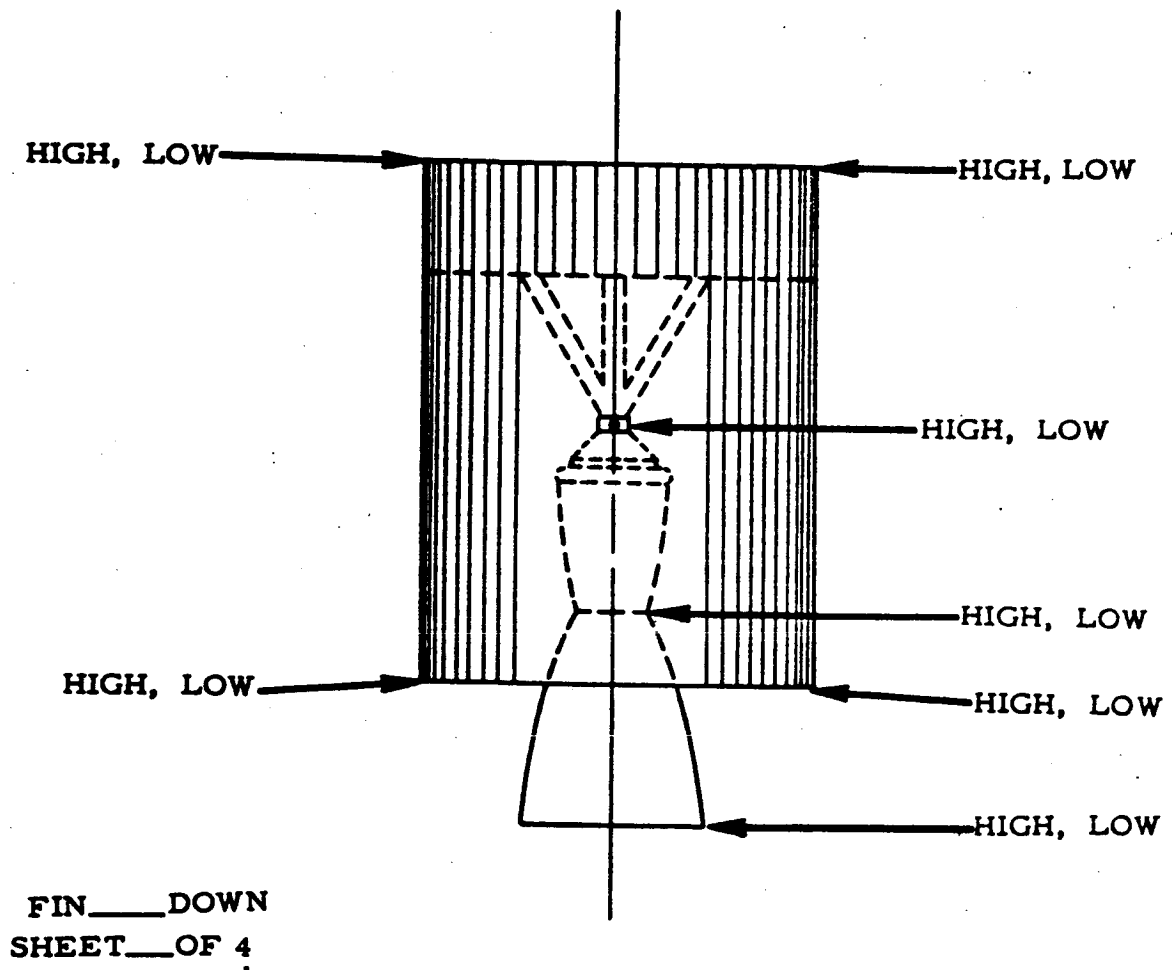


Figure 8-9. Power Unit Alignment

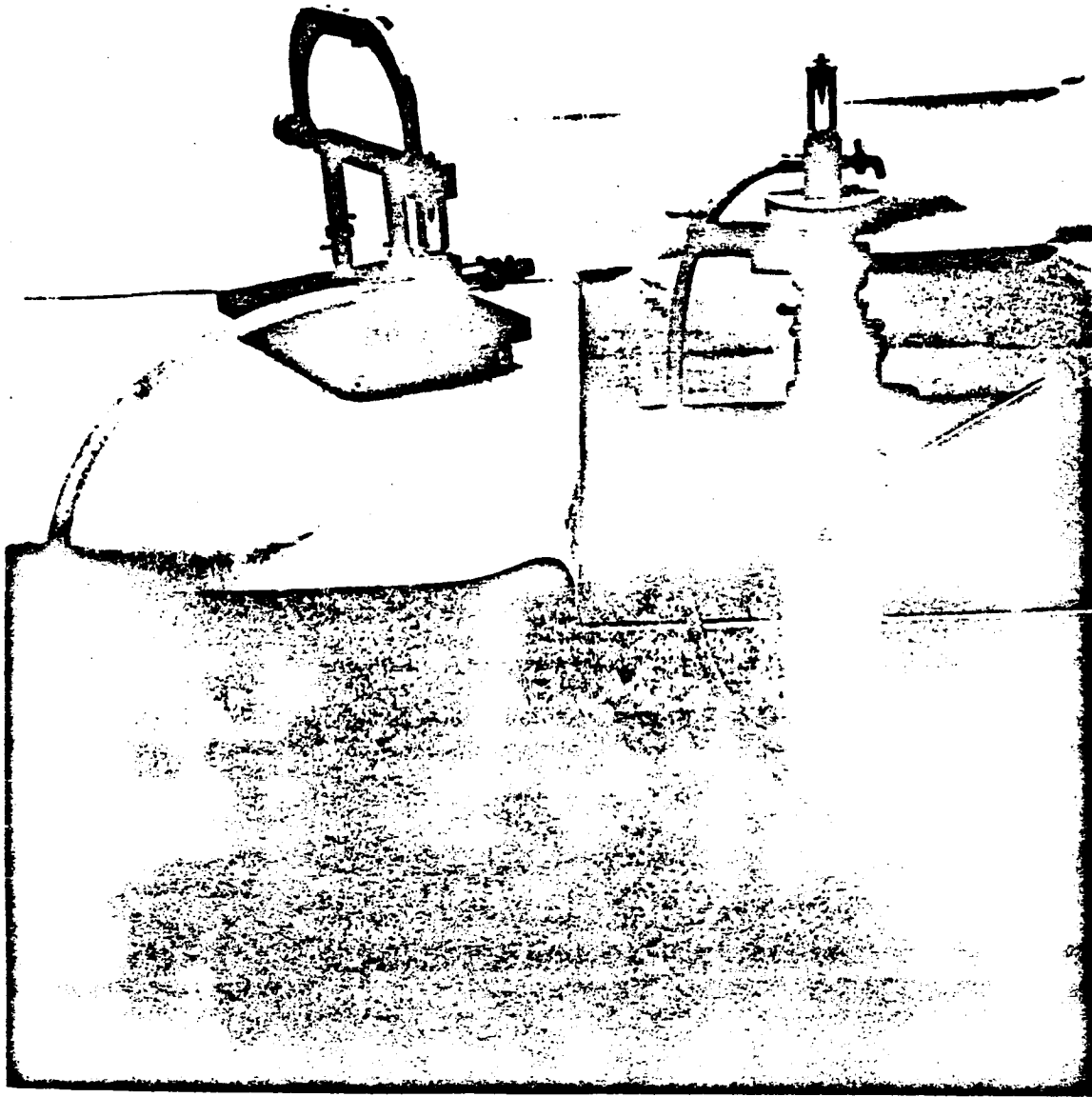


Figure 8-10. Water Level Fixture Setup

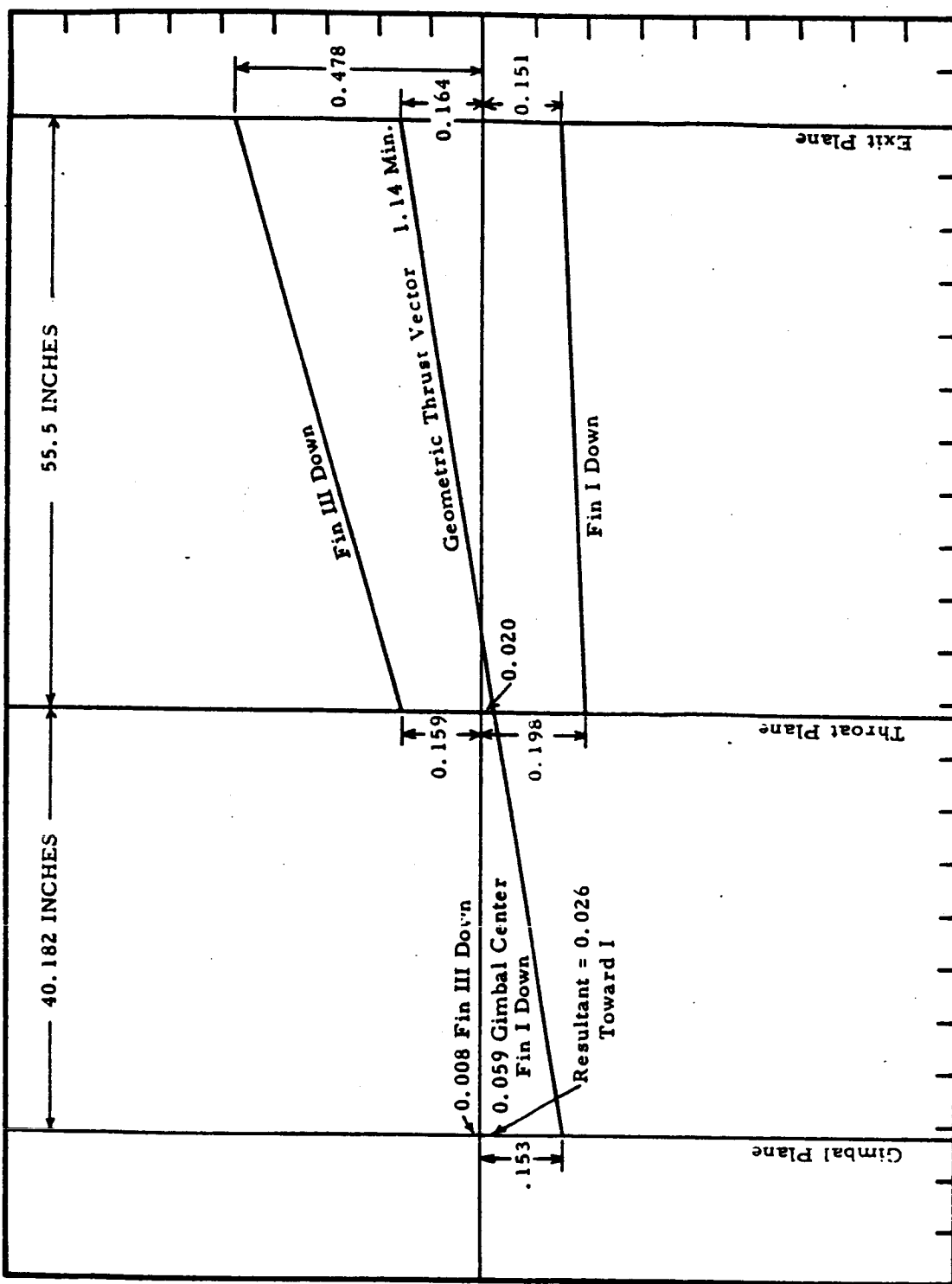


Figure 8-11. Power Unit Alignment Data, Fins I and III

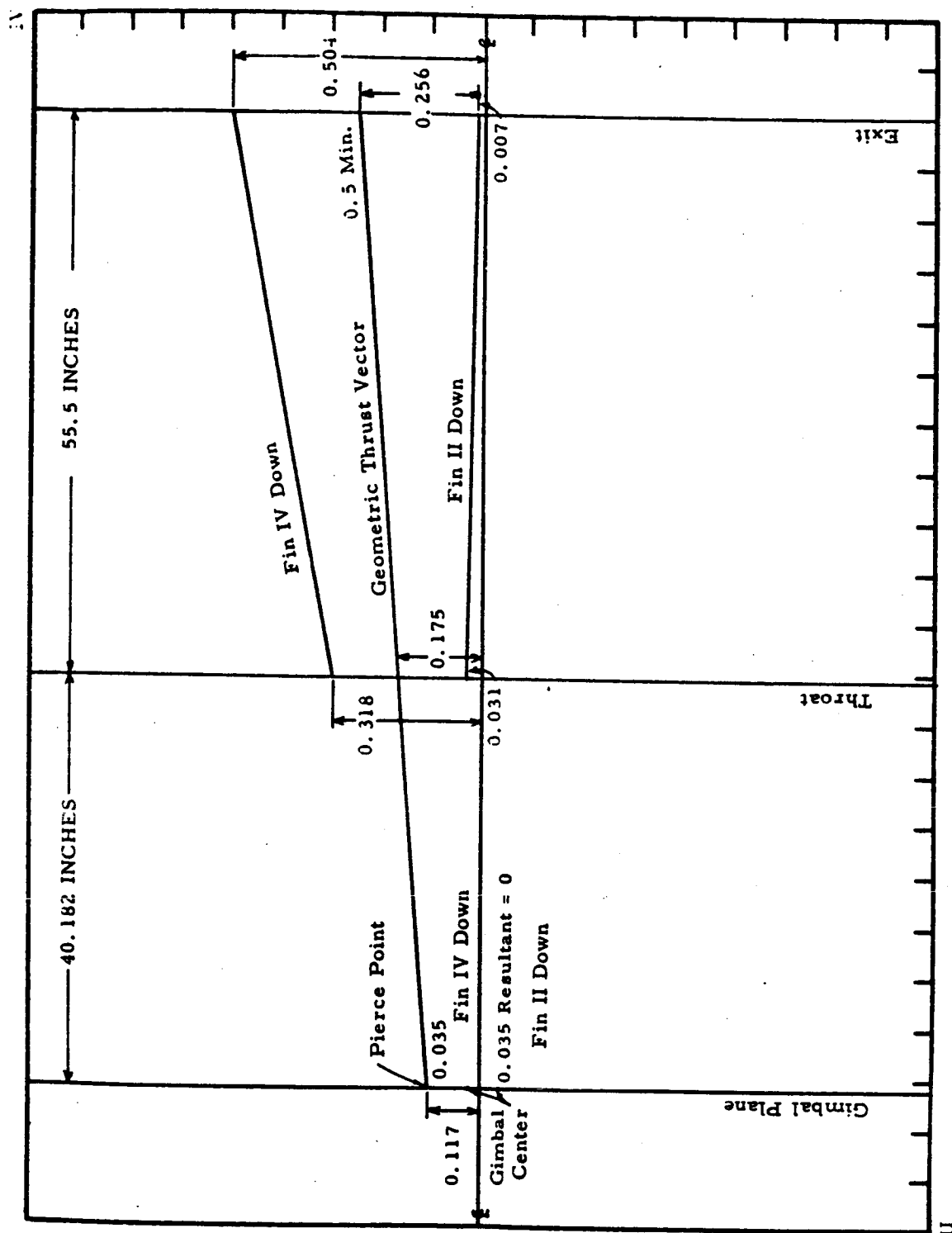


Figure 8-12. Power Unit Alignment Data, Fins II and IV

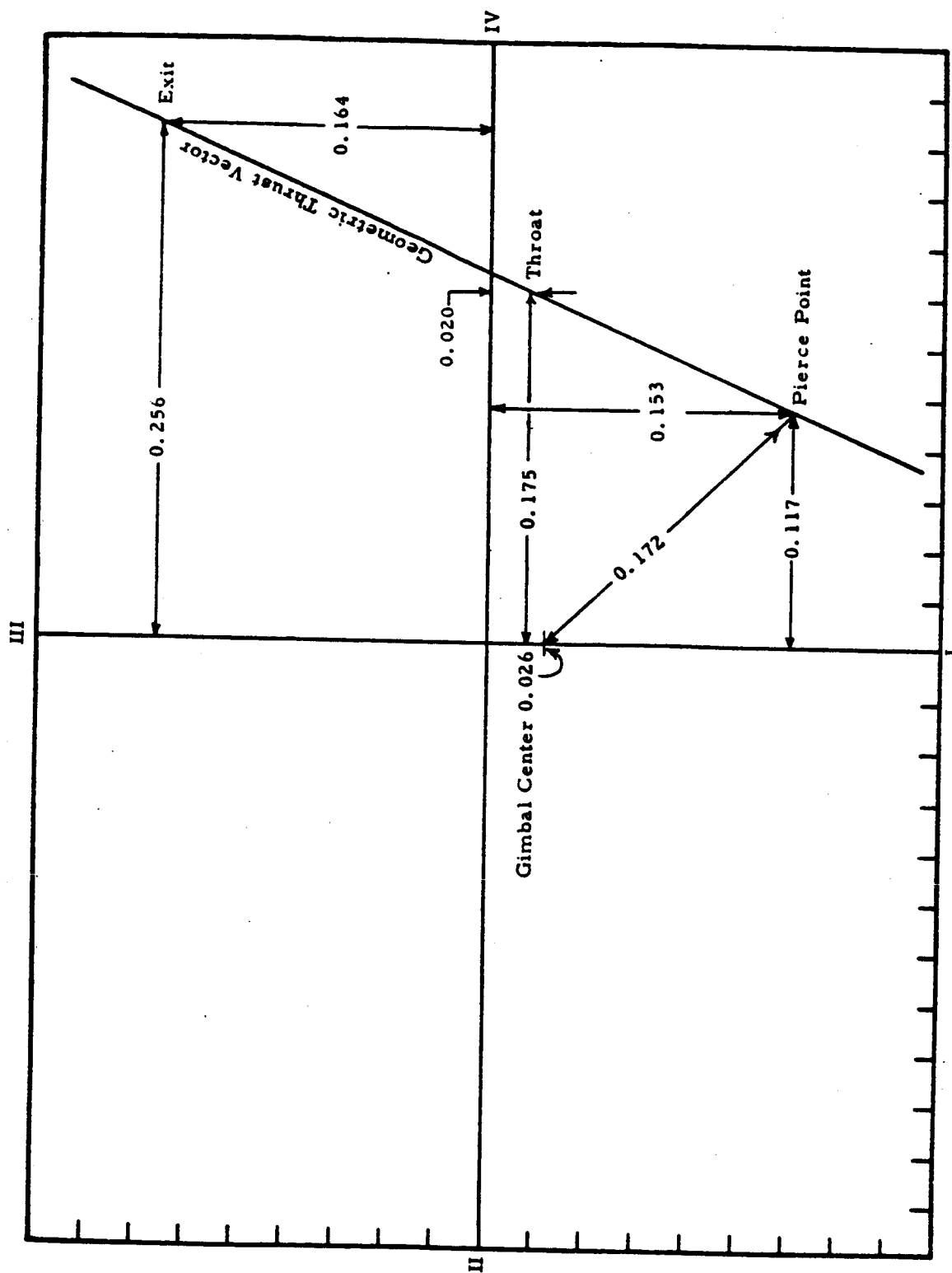


Figure 8-13. Resultant Alignment Data

## SECTION IX. VERTICAL ALIGNMENT

When the diameter of a stage is large, in proportion to its length, alignment can be accomplished in the vertical position. Since this is flight position, data obtained can be applied directly to hardware without any effect of sag. For this reason support equipment can be less elaborate than that required for horizontal alignment. One method of performing alignment in the vertical position will be described here as an example.

A hypothetical booster is 53 feet long and 22 feet in diameter. It consists of two tanks, a thrust structure, and one engine. The thrust structure which is the lower section, is 15 feet long. The lower tank is 23 feet long and the upper tank is 15 feet long. The stage centerline is perpendicular to the aft surface of the aft ring of the thrust structure, passing through its geometrical center. All components are positioned from this centerline.

During fabrication of the three sections, the center of each section is determined from structural members. Alignment targets, that mark the fin planes, are placed on the outer skin surface of each section. These targets are used as alignment references. The intersection of lines connecting the targets is the center of the section.

A layout on the floor is used as a reference system to control alignment during assembly. To make the layout, a transit would be set up in the assembly area. Four targets would be positioned on a line established by this transit. These targets would define positions I and III (Figure 9-1). Next, without moving the first instrument, a second transit would be set perpendicular to the first by auto-collimation. Four targets would be aligned with the second instrument to define positions II and IV (Figure 9-1).

Tooling required would be four transits, a sight level, 60 foot tape, 10 and 20 inch Wyteface scales, four instrument stands, a tripod, and a support fixture. The fixture would have to include reference targets, to align it with the layout, and four nest pads to support the aft ring of the thrust structure.

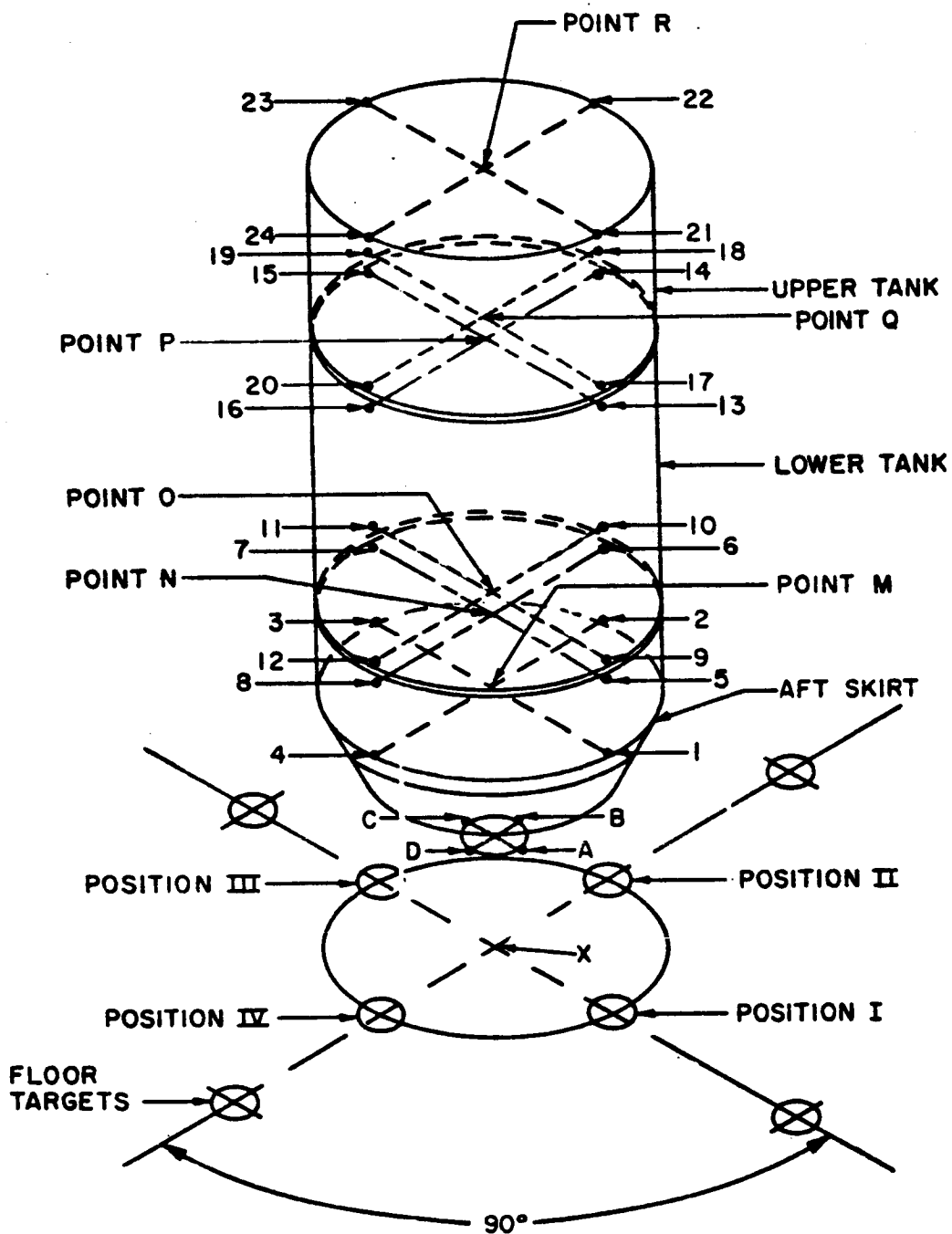


Figure 9-1. Vertical Alignment Layout

To begin alignment of the assembly, the support fixture would be positioned over the reference layout. Transits would be set up and aligned with the four positions. Then the support fixture would be aligned using these transits. Next the fixture would be leveled using the sight level. The tape would be suspended where it could be sighted with the sight level. Weights to apply the proper tension would be attached. Proper amount of weight can be obtained from the tape manufacturer. Next the thrust structure would be set on the support fixture. Targets at positions 1 and 3 (Figure 9-1), would be aligned with reference positions I and III. Then targets 2 and 4 (Figure 9-1), would be aligned with positions II and IV.

In installing these targets some tolerance must have been used. For this reason it will not be possible to have all four targets aligned with their respective reference targets. Any difference between targets 2 and 4, and positions II and IV must be split out. That is, the thrust structure would be moved until targets 2 and 4 would be equal distances from the reference line but in opposite directions. When target 1 is aligned with position I, target 3 with position III and targets 2 and 4 split out about positions II and IV, point M will be aligned over point X. Since the aft ring is supported by the fixture, and the fixture is level, the stage center line is vertical and passes through points X and M.

After the thrust structure has been positioned, the lower tank is installed. It would be aligned, using the reference targets in the same manner that the thrust structure was. Then the upper tank would be installed and aligned. Table 9-1 illustrates instrument readings resulting from different locations of the points to be measured.

Other data to be obtained during this alignment is stage length, distance from plane A to engine gimbal pad, and parallelism of forward interface and plane A. Figure 9-2 shows instrument arrangement for this. Table 9-2 is an example of scale and tape readings with the resulting distances.

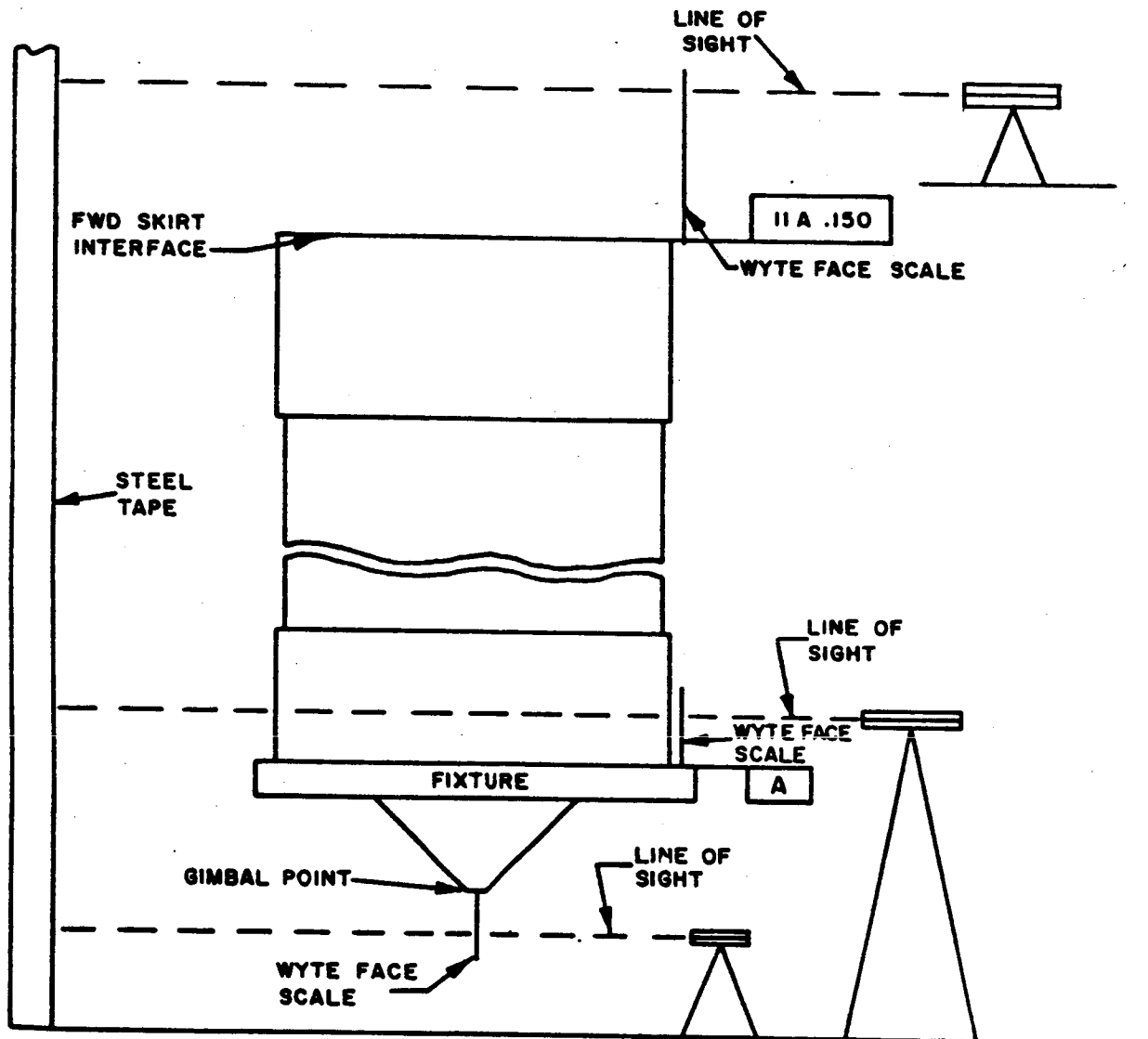
Table 9-1. Instrument Readings

<u>MEASUREMENTS</u>			
A	.035 to II	15	.010 to II
B	.040 to I	16	.020 to III
C	.045 to IV	17	.065 to II
D	.030 to I	18	.045 to III
1	.045 to II	19	.035 to II
2	.050 to III	20	.020 to I
3	.035 to IV	21	.100 to II
4	.020 to III	22	.125 to III
5	.035 to II	23	.110 to II
6	.040 to III	24	.120 to I
7	.020 to IV		
8	.010 to III	Gimbal Center $\oplus$	.060 to M
9	.035 to IV	N $\oplus$	.050 to M
10	.015 to I	O $\oplus$	.050 to M
11	.030 to II	P $\oplus$	.200 to M
12	.040 to III	Q $\oplus$	.200 to M
13	.010 to IV	R $\oplus$	.300 to M
14	.025 to I		

Table 9-2. Scale and Tape Data

	<u>POS I</u>	<u>POS II</u>	<u>POS III</u>	<u>POS IV</u>
Scale Readings				
Fwd Interface	6.335	6.320	6.325	6.330
Fwd Skirt				
Scale Readings				
on Support	2.430	2.425	2.412	2.440
Fixture				
	Top	Center	Floor	
	Elevation	Elevation	Elevation	
Dimensions on				
Steel Tape	600.000	120.000	10.000	
Scale Reading				
at Gimbal Point	6.995	9-4		

### Length from Plane A to Gimbal Point



**Figure 9-2. Elevation**

## SECTION X. DETERMINATION OF FLATNESS OF CANTED PLANE

This section describes one method of determining flatness of a canted plane. The method can be applied to any object when flatness must be known, and the plane to be measured can not be physically leveled or made vertical. The object in this case will be the forward interface of the Saturn S-1 model (Figure 10-1).

The forward interface of this stage is the spider beam assembly. This assembly has a pad at each fin position and at each 45 degree position between the fin positions. These eight pads form a plane for supporting the next stage. This plane must be flat within 0.060 inch and perpendicular to the center line of the stage within 3 minutes. Since this must be measured with respect to the center line, the position of the center line must be known in two planes.

The center line of the S-1 stage is defined as passing through the geometric center of each end ring. The spider beam is the forward ring and the thrust section is the aft ring. During manufacture of these assemblies, optical targets were placed on the structure to establish the reference system. On the spider beam targets, at each fin position, establish the center of that assembly. A fixture in the thrust structure has an optical target on it which establishes the center of that section.

To check flatness and angularity of the spider beam, bring the center line under optical control in two planes. The method of accomplishing this will be left to the reader as a problem.

### NOTE

Draw a diagram of a method which can be used to accomplish this. This will be a horizontal alignment.

1. Set up a transit so that its plane of sight is perpendicular to the stage center line and forward of the spider beam. Have an assistant hold a scale against each of the eight pads so the distance from the reference plane to each pad can be measured. Measure to three locations of each pad, one in the center and one on each end. Record the readings on the data sheet (Figure 10-2). Rotate the stage 180 degrees and again bring it under control. Repeat the measurements and record data.



Figure 10-1 Model

**FOREWARD SPIDER BEAM**

+ IS FOREWARD  
 - IS AFT

PLANER QUALITY \_\_\_\_\_  
 PITCH PLANE ANGLE \_\_\_\_\_  
 YAW PITCH ANGLE \_\_\_\_\_

FIN _____ DOWN						
PAD POSITION	INSTRUMENT READING			AVERAGE READING	VARIATION IN READING	DIFFERENCE FROM REFERENCE
	FIRST	SECOND	THIRD			

FIN _____ DOWN						
PAD POSITION	INSTRUMENT READING			AVERAGE READING	VARIATION IN READING	DIFFERENCE FROM REFERENCE
	FIRST	SECOND	THIRD			

Figure 10-2. Alignment Data  
10-3

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2. Average the three readings, recorded on Figure 10-2 that were taken at each spider beam position with fin I down. Select one of the average values to be used as a basic reference. For the purpose of this procedure the most forward average value was taken. (Forward will be plus and aft will be minus.)

3. Determine the displacement at each fin and 45 degree position, and record in a table as shown in Table 10-1.

Table 10-1.

Spider Beam Planer Quality Data

<u>Position</u>	<u>Fin I Down</u>	<u>Fin III Down</u>	<u>Sag Factor</u>	<u>Free State</u>
I	-0.009	-0.018	0.005	-0.013
I-II (45°)	-0.014	-0.076	0.031	-0.045
II	-0.033	-0.104	0.036	-0.068
II-III (45°)	-0.038	-0.118	0.045	-0.073
III	-0.076	-0.144	0.034	-0.110
III-IV (45°)	-0.053	-0.056	0.001	-0.055
IV	0.000	0.000	0.000	-0.000
IV-I (45°)	-0.006	-0.013	0.003	-0.010

4. Average the three readings, recorded on Figure 10-2 that were taken at each spider beam position with fin III down. Use the same position for the basic reference that was used with fin I down.

5. Determine the displacement at each fin and 45 degree position as shown in Table 10-1 column 3.

6. Determine and remove the sag factor from the values given with fins I and III down. If the two values are in the same direction, subtract the values and divide by 2. The remainder will be the sag factor. Record the sag factor in Table 10-1 column 4. To determine the free state position, subtract the sag factor from the larger value, as shown in the following example:

**EXAMPLE:**

Value with fin I down = 0.009 aft

Value with fin III down = 0.018 aft

$$0.018 - 0.009 = 0.009$$

$$0.009 \div 2 = 0.0045 \text{ or } 0.005 \text{ sag factor}$$

$$0.018 - 0.005 = 0.013 \text{ aft free state position}$$

**NOTE**

Since the two average readings are aft of the true position of the average position, fin I is 0.013 aft of the point at fin IV. Repeat the preceding process until the sag is removed from all positions.

7. If the two average readings should be in opposite directions, the sag factor can be found by adding the two readings and dividing the sum by two. To obtain the true position of the point, subtract the sag factor from the larger value, or subtract the smaller value from the sag factor. The direction will be toward the larger reading. In the example below, the average reading with one position down is forward 0.034; when the S-I Stage is rotated 180 degrees, the same position average reading is aft 0.026.

**EXAMPLE:**

$$0.034 + 0.026 = 0.060$$

$$0.060 \div 2 = 0.020 \text{ sag factor}$$

$$0.034 - 0.020 = 0.014 \text{ forward}$$

**NOTE**

Since the larger value is forward, the direction will be forward.

$$0.014 \text{ forward} = \text{true position}$$

8. After the sag has been removed and the true relation of all points has been established, this data must be plotted on Figure 10-2. Copy data to work sheet (Figure 10-3). Only one method to establish the true planer qualities will be discussed in this procedure. The method used in this procedure is based on the fact that when a line, or plane is pivoted about an axis, the points at equal distances from the fulcrum point, or line, move the same amount, but in opposite directions.

9. Determine the diameter with the greatest difference between the values. Refer to Figure 10-3, which shows the greatest difference between points at fin I and fin III. The diameter which is perpendicular to the fin I-III line (II-IV) will become the fulcrum about which the entire plane will be pivoted.

10. Determine the difference between the values on the I-III line ( $0.110 - 0.13 = 0.097$ ). Divide the difference by two ( $0.097 \div 2 = 0.0485$  or  $0.048$ ). Adjust the two points at fin I and III by adding  $0.048$  to the smaller (fin III) and subtracting  $0.048$  from the larger (fin I) (Figure 10-4). The value to be applied to the 45 degree positions is found by:  $\sin 45^\circ \times \text{correction at } 90^\circ$ , or,  $0.707 \times 0.048 = 0.034$ . Since the semicircle is tilted about the fulcrum, the correction will have the same sine as the 90 degree correction. Determine the difference between the largest and smallest corrected values at all 8 points. This is the planer quality at this correction.

11. Further corrections can be made by determining the diameter with the greatest difference, and repeating the process given above. Figure 10-4 shows the points at fins II and IV as having the greatest difference. In this case, the line from fin I to fin III becomes the fulcrum. Repeat the above process until the smallest difference between the 8 points is obtained. This will then be the true planer quality with the tilt angle removed (Figure 10-5).

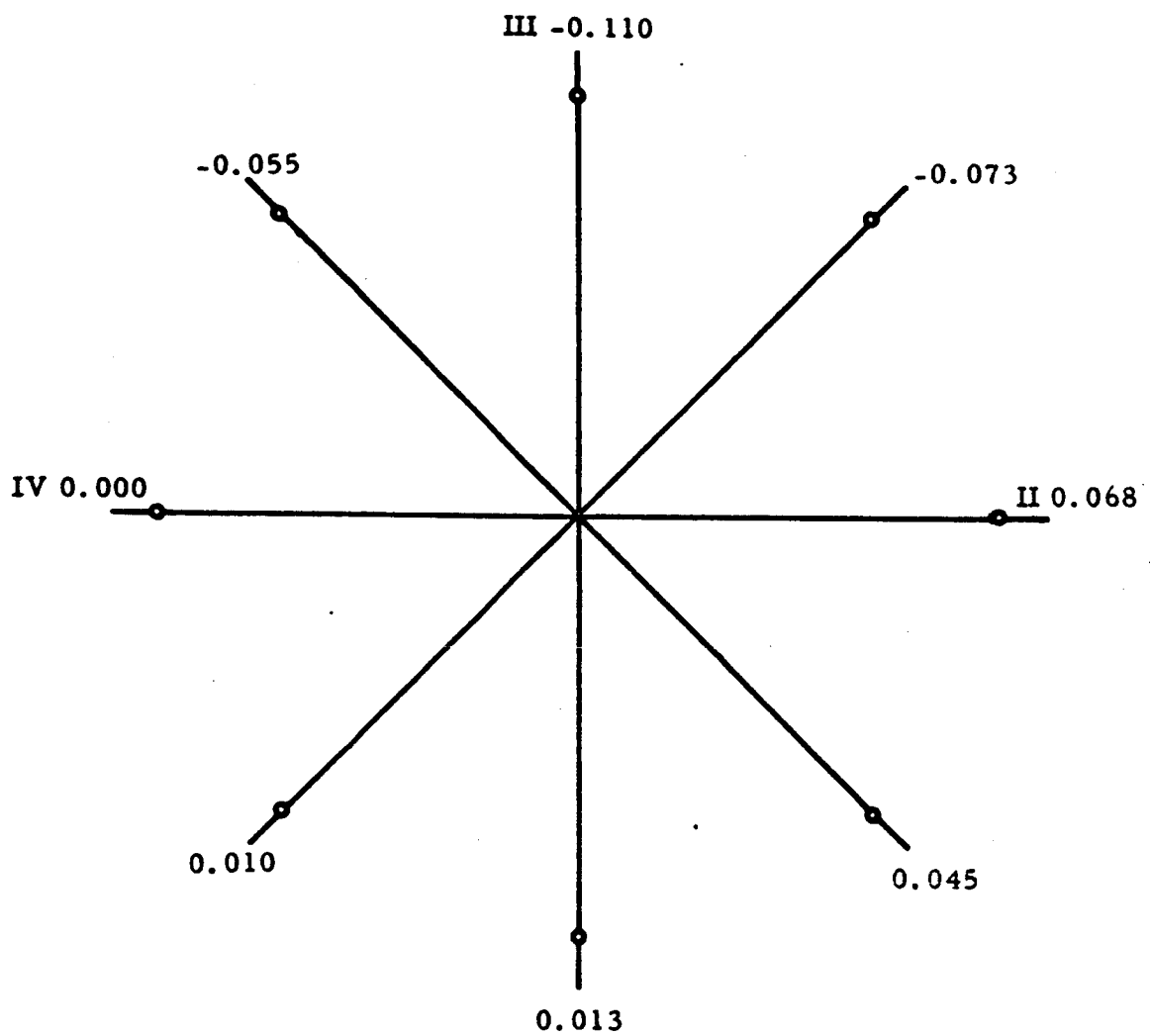


Figure 10-3. Planer Qualities Work Sheet

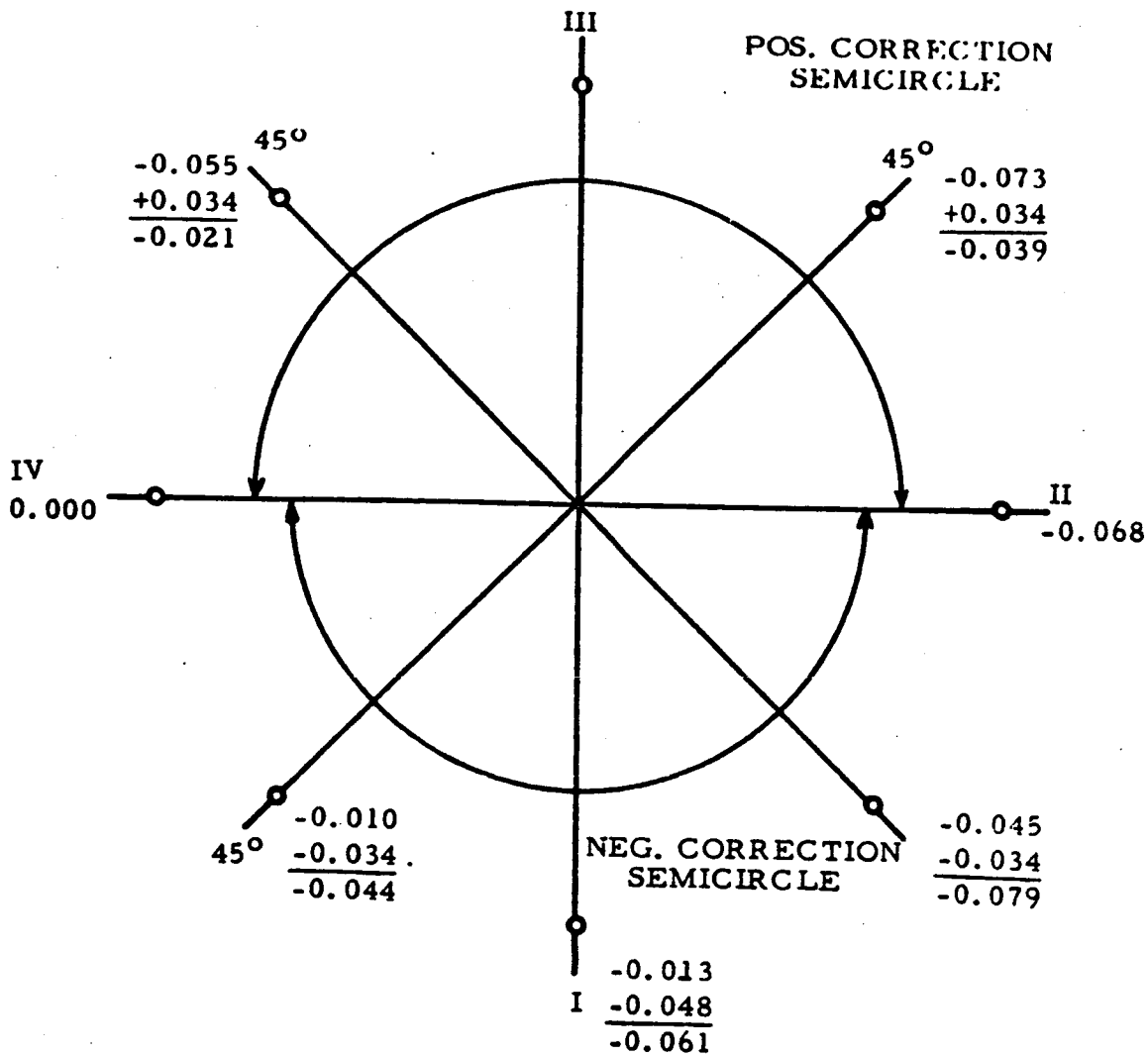


Figure 10-4. Planer Qualities 0.079  
10-8

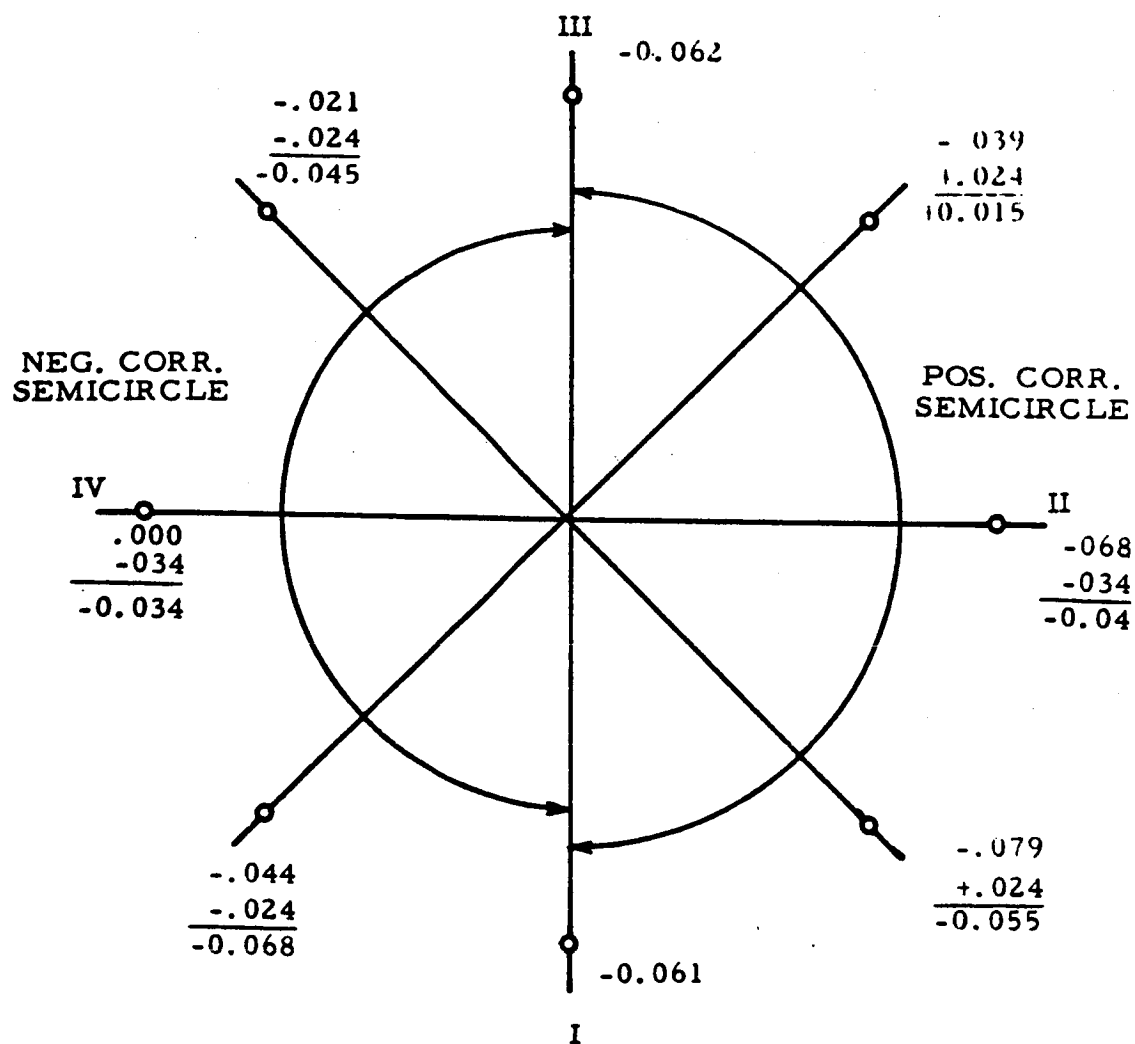


Figure 10-5. Planer Qualities 0.053

## SECTION XI. ESTABLISHING A TRUE NORTH LINE BY OBSERVATION OF POLARIS

### A. Introduction

The purpose of this procedure is to give a method to establish a true north bearing for a given location.

The bearing of Polaris may be established by several methods, two of which will be discussed in this procedure.

- (1) Observation of Polaris at elongation.
- (2) Observation of Polaris at any time (dusk to dawn).

Observation of Polaris at elongation should not be used if the required accuracy of the True North line is less than 5 minutes.

If a precise line is to be established, the method "Observation of Polaris at any time" should be used. The accuracy is established by the average of several readings.

The methods described in this procedure are considered accurate in the latitudes which include the United States mainland.

In the following discussion regarding optical instrument positioning, "bucking-in", "dumping", and "leveling-out" techniques will not be included. It is assumed that this is a basic part of the background required of personnel operating the optical instruments.

### B. Equipment Requirements

<u>Item</u>	<u>Description</u>	<u>Make**</u>	<u>Model</u>	<u>Quantity</u>
1.	Instrument Stand	Bruning	230-2	1
2.	Adapter Cap		85M04301	1
3.	Theodolite	Wild	T-3	1
4.	Radio	Hammarlund	HQ-140-XA	1
5.	Clock	General Electric	WC-12	1
6.	Lamp Power Supply	Wild	XT2-74	1

\* See Figures 11-1 and 11-2 which show the equipment used in the execution of this procedure.

\*\* All items referred to by "Brand Name" may be substituted by other "Brands" of equal quality and capability.

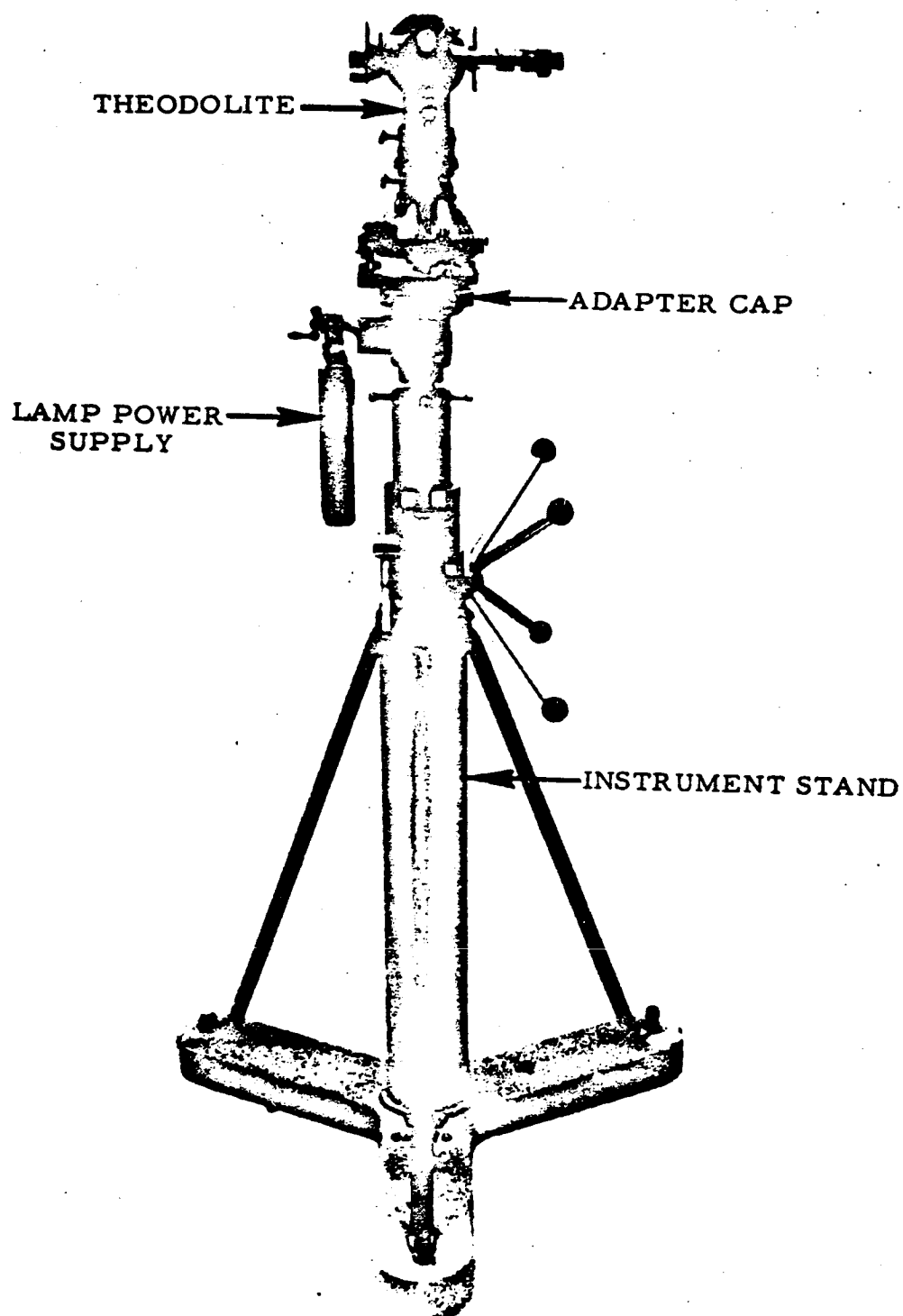


Figure 11-1. Optical Instrument Used for  
Celestial Observations

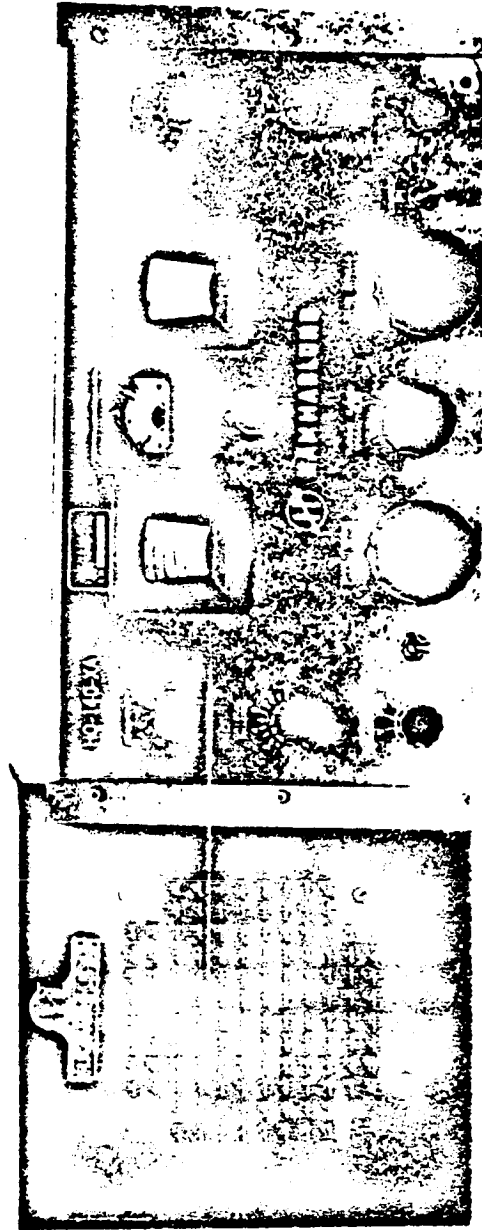
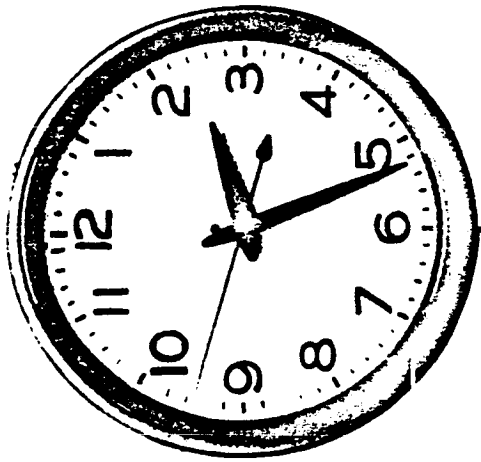


Figure 11-3. Equipment Required to Obtain Correct Time

## C. Concepts

To simplify the determination of a true north bearing, certain concepts of the heavens have been generally adopted. They are listed below:

(1) The earth is stationary.

(2) The heavenly bodies have been projected outward, along lines which extend from the center of the earth, to a sphere of infinite radius called the celestial sphere which has the following characteristics:

(a) Its center is the center of the earth.

(b) Its equator is on the projection of the earth's equator.

(c) With respect to the earth, the celestial sphere rotates from east to west about a line which coincides with the earth's axis. The poles of the celestial sphere are the earth's poles extended.

(d) The speed of rotation of the celestial sphere is  $360^{\circ} 59.14'$  per 24 hours.

(e) Except for the bodies in the solar system, which change positions slowly, all heavenly bodies remain practically fixed in their relative position, changing negligible amounts in 24 hours.

### 1. A Spherical Triangle.

A great circle is the trace on a sphere of a plane which passes through the center of the sphere. A spherical triangle is the figure on a sphere bounded by the arcs of three great circles. It has six parts: three sides and three angles. When any three parts are known, the other three can be found. Both sides and angles are measured in angular units, usually in degrees and minutes. The length of a side is measured by the angle at the center of the sphere between the radii extended to its ends. The size of an angle is measured by the dihedral angle between the planes of the great circles which form it. It may also be measured by the angle between the tangents to the great circles at their intersection.

Any three points on a sphere may be joined by great circles to form a triangle in which no part is greater than  $180^\circ$ . Such a triangle is the one always considered in this text.

## 2. The Principles

Figure 11-3 illustrates the spherical trigonometry involved in every observation for position or for true north. It represents the conditions that exist at the moment of observation. P is a pole of the celestial sphere (in this case the north pole), \* S is the celestial body observed (the arrows represent the path of the body) and Z is the observer's zenith. The lines joining them are arcs of great circles.

## 3. The Zenith

The observer's zenith is a point on the celestial sphere found by projecting the center of the instrument at the time of observation upward along the direction opposite to that of gravity.

## 4. The Astronomical Triangle (Figure 11-3)

The triangle PZS is known as the astronomical triangle. It may be formed west of the meridian as shown, or east of the meridian if the body is so located. It is a true spherical triangle formed by great circles, and spherical trigonometric formulas apply. When Z or S, or both, are in the southern hemisphere, other arrangements are created. Figure 11-4 shows the twelve possibilities. Note that no angle or side is greater than  $180^\circ$ . All forms of the triangle are solved by the same formulas but the results of the solutions do not indicate whether the body is east or west of the meridian. This can be determined from the LHA described in the next paragraph. The six parts of the triangle are named and described below.

Angle t is known as the meridian angle. The Local Hour Angle (LHA) of a body is the angle measured westward around the axis of the celestial sphere from the meridian of the observation to the meridian of the body. The arc MA represents the LHA. Obviously

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\* The south pole may be used, but signs of the latitude and the declination must then be reversed. To avoid confusion, the symbol P in this text is always taken as the north pole.

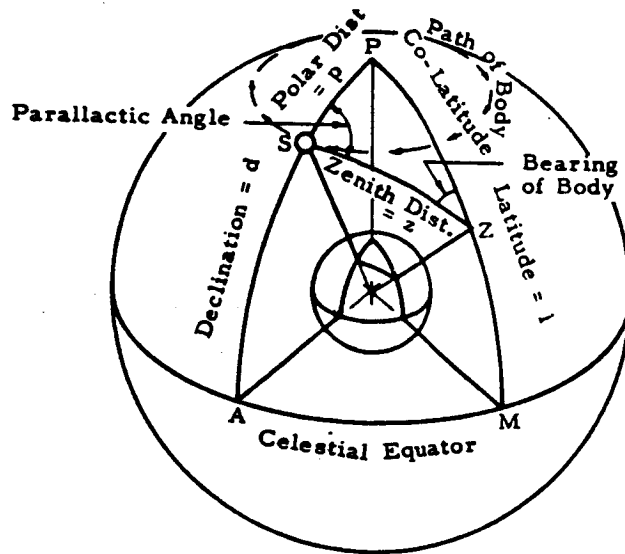
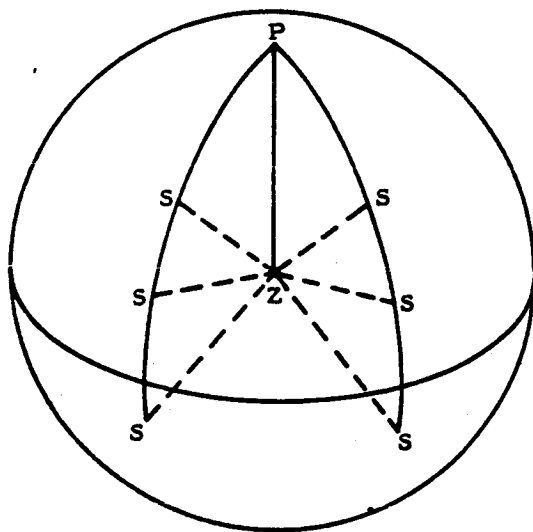
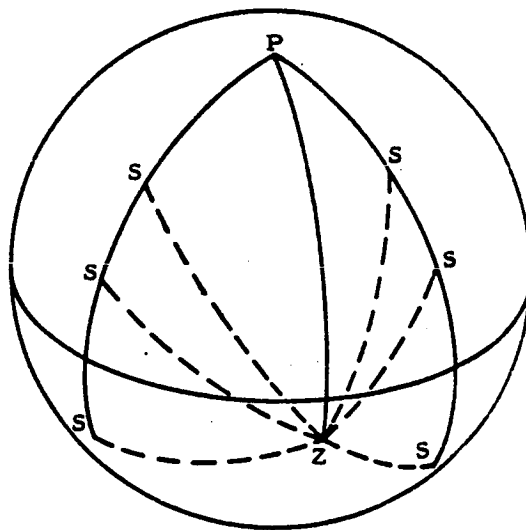


Figure 11-3. The Astronomical Triangle



Observer in Northern Hemisphere



Observer in Southern Hemisphere

Figure 11-4. Observer in Northern and Southern Hemisphere

$$\text{LHA} = \text{GHA} - \text{West Longitude} \dots\dots (2)$$

$$\text{LHA} = \text{GHA} + \text{East Longitude} \dots\dots (2a)$$

When the LHA is less than  $180^\circ$ , the body is west of north and:  $t = \text{LHA}$

When the LHA is greater than  $180^\circ$ , the body is east of north and:  $t = 360^\circ - \text{LHA}$

Angle Z is the bearing \* of the body S, since it is equal to the horizontal angle between the north direction of the observer's meridian and the direction of the body. It is measured east or west of north according to the position of the PZS triangle.

Angle S is the parallactic angle. It is usually unnecessary to use the value of this angle.

Side PS (p) is the polar distance. It is equal to  $90^\circ$  minus the declination (d) of the body S. In the formulas used for many observations  $\sin d$  is substituted for  $\cos p$ , etc.

Side PZ is the co-latitude of Z. It is equal to  $90^\circ$  minus the latitude (l) of the observer. The formulas are often written using  $\sin l$  substituted for  $\cos$  co-latitude, etc.

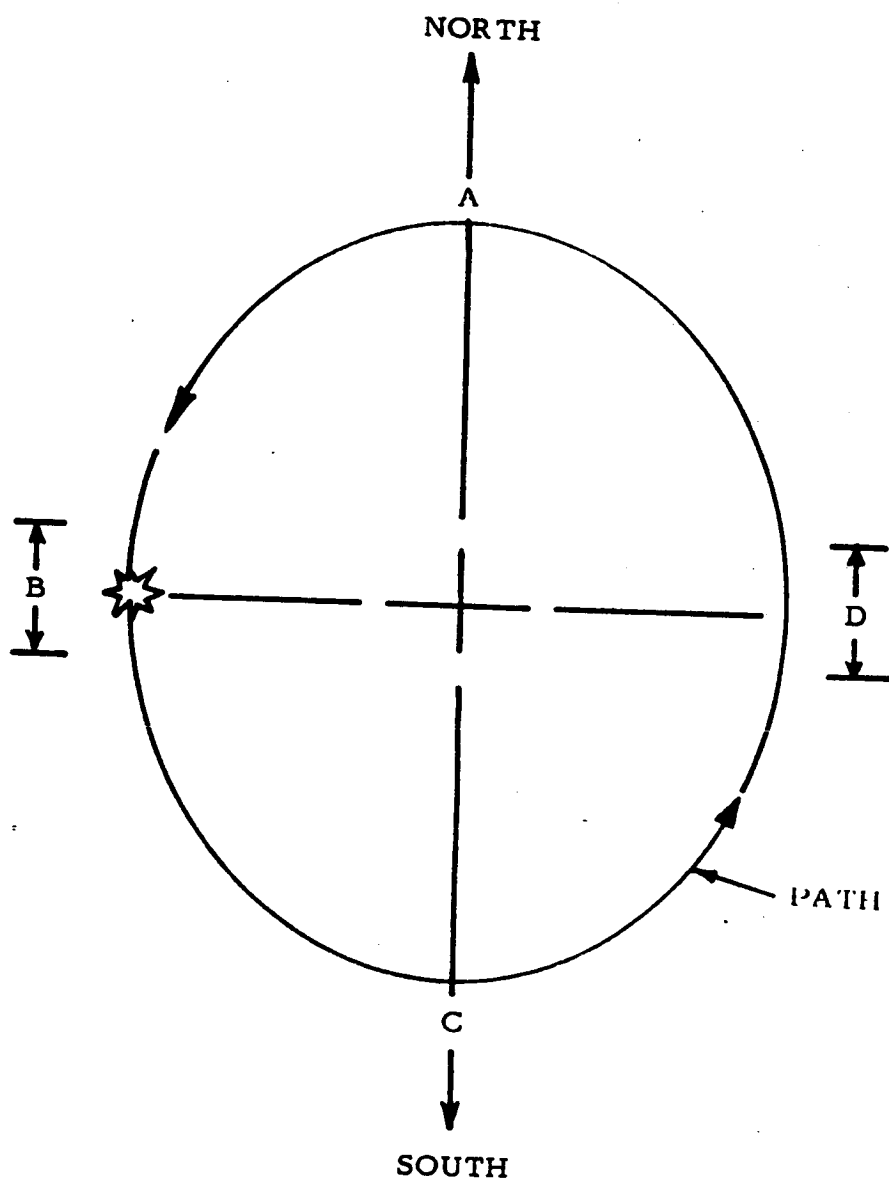
Side ZS (z) is the zenith distance of the body S. It is equal to  $90^\circ$  minus true altitude (h). The true altitude can be found in the field by observing the altitude of a body and correcting the result for refraction and parallax.

#### D. General Information

Polaris appears to travel in a counterclockwise circular path about the North Pole. The point in the path where Polaris is further east or west is called eastern or western elongation, respectively, and where in the path it is directly over the Pole (True North) it is called upper or lower culmination (Figure 11-5). At eastern, or western elongation, Polaris travels in an apparent vertical line for a

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\* The term bearing is used here in preference to azimuth since the angle measured from the north may be either east or west. It may exceed  $90^\circ$  but is always less than  $180^\circ$ .



# LEGEND

A-UPPER CULMINATION\*\*  
B-WESTERN ELONGATION\*

C-LOWER CULMINATION\*\*  
D-EASTERN ELONGATION\*

\*VERTICAL TRAVEL TIME EQUALS APPROXIMATELY 20 MIN.  
\*\*ACTUAL TRUE NORTH BEARING

Figure 11-5. Movement of Polaris Over North Pole

period of approximately 20 minutes. During this time the observer will be able to take a reading, dump the scope, and read again at the same azimuth angle. This will eliminate any error in the instrument by taking an average of the two readings.

The position of a heavenly body with respect to the earth, at any given time, is given by its declination and its Greenwich Hour Angle (GHA) (Figure 11-6).

A declination is equivalent to a latitude, and is plus (+) angular distance measured north from the equator. Tables for declination of Polaris are given in a Solar Ephemeris.

The polar distance of a body is equal to  $90^\circ$  minus the declination of the body (Table 11-1).

The Greenwich Hour Angle (GHA) is the angle measured from the meridian of Greenwich westward to the meridian over which the body stands at any moment. Up to  $180^\circ$ , a GHA is equivalent to west longitude, and thereafter, it continues up to  $360^\circ$ .

The GHA's of Polaris are always increasing as the heavens move toward the west. A Solar Ephemeris gives a table of the GHA's of Polaris at the moment of Greenwich midnight zero hour ( $0^h$ ) for each day of the year.

Since the angular speed of rotation of the celestial sphere is known, the increase in the GHA that occurs at Greenwich  $0^h$  can be computed for any time of day. Increase in GHA for Elapsed Time is given in Table 11-7.

Time has two meanings that are often confused: elapsed time and moment of time.

The measure of elapsed time used in this procedure is the familiar hour of which there are 24 in a day. Elapsed time, so measured, is called Civil Time (CT).

(1) Greenwich Civil Time (GCT) is civil time reckoned from  $0^h$  Greenwich Meridian,  $0^\circ$  longitude; 90th meridian time (Central Standard Time, CST) is civil time reckoned from midnight at the 90th meridian,  $90^\circ$  longitude.

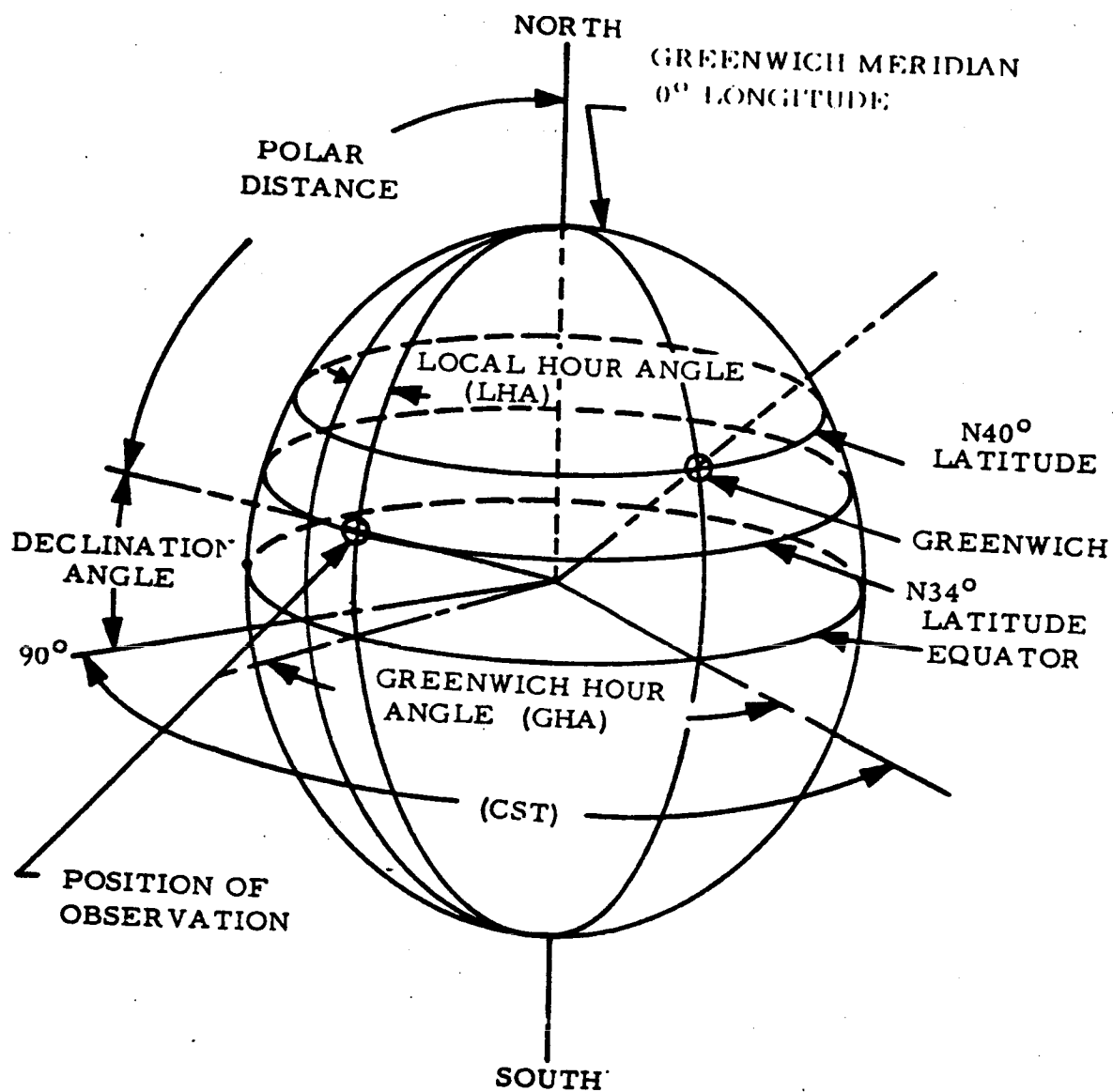


Figure 11-6. Hour Angles Referenced From Meridian of Greenwich  
11-10

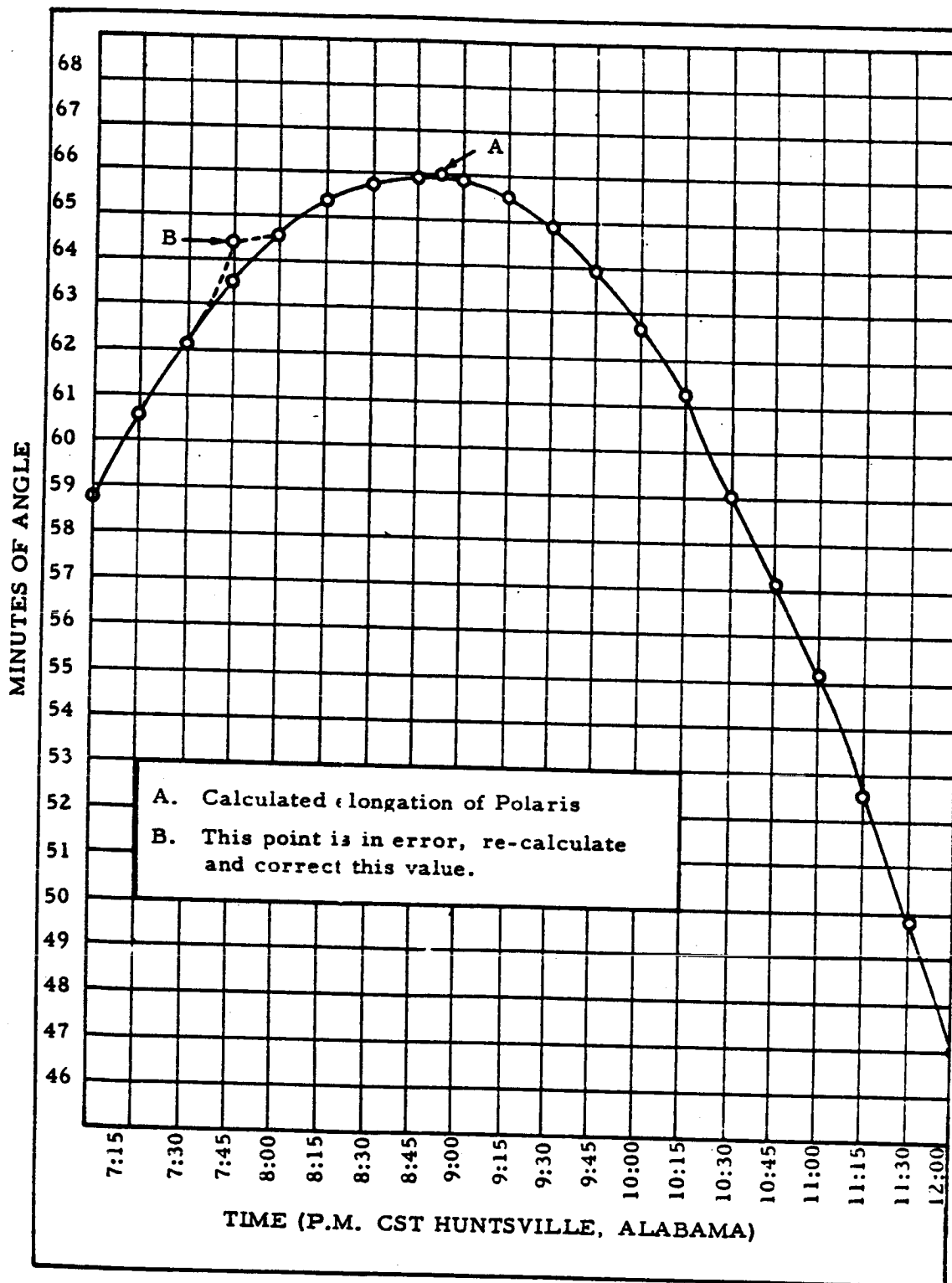


Figure 11-7. Calculated Bearing of Polaris, September 5, 1964

(2) Local Civil Time (LCT) is the civil time reckoned from the precise meridian of longitude where the observation is taken.

A moment of time is given by the year, the day of the month, and the elapsed time since midnight (0<sup>h</sup>) at the beginning of the day named, and the meridian from which it is reckoned.

Since the tables given in the Solar Ephemeris are based on Greenwich, which is 0° longitude and N40° latitude, great care must be used in calculating the values. Interpolation must be used for all fractional values. The tables change from year to year; therefore, current tables must always be used.

## E. Methods of Observation

### 1. Observation of Polaris at Elongation

a. Determine the precise latitude and longitude for the point of observation from a Geodetic Survey Grid Map.

b. Two methods for calculating the true north bearing of Polaris at Elongation should be used as a check. The two methods should agree within 20% of the desired accuracy of the line.

(1) Calculate the bearing of Polaris by double interpolation of bearing of Polaris from Table 11-2.

(2) Calculate the bearing of Polaris by the formula:

Bearing of Polaris =

$$\frac{\text{Polar distance in minutes (Table 11-1)}}{\text{Cosine of the Local Latitude}}$$

c. After the calculations have been completed for the bearing of Polaris, the time of elongation must be found.

(1) Determine the GCT of elongation for the date of observations from the Solar Ephemeris.

(2) Correct GCT to Local Standard Time (LST).

(a) Correct GCT of elongation for the precise latitude as found in Table 11-3.

(b) Correct GCT to precise LST. Add  $0.011^m$  for each degree east of Greenwich; subtract  $0.011^m$ , if west.

(c) Correct LST to standard time by adding  $4^m$  for each degree the local meridian is west of the standard time meridian; subtract if east. The result will be the exact standard time of elongation for the local meridian.

## 2. Observation of Polaris at Any Time

a. Determine the precise latitude and longitude for the point of observation from a Geodetic Survey Grid Map.

b. Calculate the bearing (azimuth angle) that Polaris will be off True North for each time the reading is to be taken. Use the formula:

$$Z = \frac{\sin t}{\cos h} \quad P, \text{ where } Z = \text{Bearing of Polaris} \quad t = \text{Meridian Angle}$$

$P = \text{Polar Distance} \quad h = \text{True Altitude}$   
(Minutes of Angle)

## F. Examples of Calculations

### 1. Calculation for Observation of Polaris at Elongation

a. Determine the precise latitude and longitude for the point of observation from a Geodetic Survey Grid Map.

(1) The precise latitude is  $34^{\circ}39'07''$

(2) The precise longitude is  $86^{\circ}40'42''$

### NOTE

For the purpose of this procedure September 5, 1964, has been selected for all sample calculations.

b. Bearing of Polaris from True North at Elongation.

(1) Calculation of the Bearing of Polaris by double interpolation:

(a) Interpolate polar distance for September 5, 1964, from Table 11-1.

August 28       $0^{\circ}54.32'$   
September 7     $0^{\circ}54.28'$

August 28 to September 7 is 10 days, September 5 to 7 is 2 days; therefore, September 5 will be  $2/10$  of the difference between  $54.32'$  and  $54.28'$  which is  $0.004'$ .

$2/10$  of  $0.04' = 0.008'$   
 $0.008 + 54.28 = 54.288'$  or  $54.29'$   
 $0^{\circ}54.29' =$  polar distance for  
September 5, 1964

(b) Use polar distance  $0^{\circ}54.29'$ , and precise latitude  $34^{\circ}39'07''$  ( $34.65^{\circ}$ ) to double interpolate, as shown in Table 11-4, the bearing of Polaris. The bearing of Polaris at elongation for September 5, 1964, is  $1^{\circ}06.01'$  or  $1^{\circ}06'00.6''$ .

(2) Calculation of the Bearing of Polaris by formula:

$$\text{Bearing} = \frac{\text{Polar distance in minutes}}{\text{Cosine of precise latitude}}$$

Polar distance, as determined previously, is  $0^{\circ}54.29'$  for September 5, 1964. Interpolation from trigonometry tables for cosine of  $34^{\circ}39'07''$  is 0.8226.

$$\text{Bearing} = \frac{0^{\circ}54.29'}{0.82262} = 0^{\circ}65.996' \text{ or } 1^{\circ}05'59.76''$$

$1^{\circ}05'59.76''$  is the bearing of Polaris on September 5, 1964

#### NOTE

The difference between the two methods is due to rounding off the numbers during calculation.

$$1^{\circ}06'0.6'' = 1^{\circ}05'59.76'' \text{ (Difference} = 0^{\circ}0'0.84'')$$

11-14

Table 11-1

POLAR DISTANCE OF POLARIS, 1964 For 0 <sup>h</sup> Universal Time or Greenwich Time					
Polar Distance			Polar Distance		
	Angle	Cotan		Angle	Cotan
1964	°	'	1964	°	'
Jan. 1	0 53.96	63.71	July 9	0 54.44	63.15
11	0 53.93	63.74	19	0 54.43	63.15
21	0 53.92	63.75	29	0 54.42	63.17
31	0 53.91	63.76			
Feb. 10	0 53.92	63.75	Aug. 8	0 54.39	63.20
20	0 53.94	63.72	18	0 54.36	63.23
			28	0 54.32	63.28
Mar. 1	0 53.97	63.69	Sept. 7	0 54.29	63.33
11	0 54.01	63.65	17	0 54.23	63.39
21	0 54.05	63.60	27	0 54.17	63.45
31	0 54.10	63.54			
Apr. 10	0 54.15	63.48	Oct. 7	0 54.11	63.53
20	0 54.20	63.43	17	0 54.05	63.60
30	0 54.25	63.38	27	0 53.98	63.68
May 10	0 54.30	63.31	Nov. 6	0 53.92	63.75
20	0 54.33	63.26	16	0 53.86	63.82
30	0 54.37	63.22	26	0 53.80	63.90
June 9	0 54.40	63.19	Dec. 6	0 53.75	63.96
19	0 54.42	63.16	16	0 53.70	64.01
29	0 54.43	63.15	26	0 53.66	64.06

Declination = 90° - Polar Distance

Table 11-2

BEARING OF POLARIS AT ELONGATION 1964									
Polar Dist.	0° 53.80'	0° 54.00'	0° 54.20'	0° 54.40'	Polar Dist.	0° 53.80'	0° 54.00'	0° 54.20'	0° 54.40'
Lat.	Bearing at Elongation				Lat.	Bearing at Elongation			
°	'	'	'	'	°	'	'	'	'
10	0 54.6	0 54.8	0 55.0	0 55.2	40	1 10.2	1 10.5	1 10.8	1 11.0
11	0 54.8	0 55.0	0 55.2	0 55.4	41	1 11.3	1 11.6	1 11.8	1 12.1
12	0 55.0	0 55.2	0 55.4	0 55.6	42	1 12.4	1 12.7	1 12.9	1 13.2
13	0 55.2	0 55.4	0 55.6	0 55.8	43	1 13.6	1 13.8	1 14.1	1 14.4
14	0 55.4	0 55.7	0 55.9	0 56.1	44	1 14.8	1 15.1	1 15.3	1 15.6
15	0 55.7	0 55.9	0 56.1	0 56.3	45	1 16.1	1 16.4	1 16.7	1 16.9
16	0 56.0	0 56.2	0 56.4	0 56.6	46	1 17.5	1 17.7	1 18.0	1 18.3
17	0 56.3	0 56.5	0 56.7	0 56.9	47	1 18.9	1 19.2	1 19.5	1 19.8
18	0 56.6	0 56.8	0 57.0	0 57.2	48	1 20.4	1 20.7	1 21.0	1 21.3
19	0 56.9	0 57.1	0 57.3	0 57.5	49	1 22.0	1 22.3	1 22.6	1 22.9
20	0 57.3	0 57.5	0 57.7	0 57.9	50	1 23.7	1 24.0	1 24.3	1 24.6
21	0 57.6	0 57.8	0 58.1	0 58.3	51	1 25.5	1 25.8	1 26.1	1 26.4
22	0 58.0	0 58.2	0 58.5	0 58.7	52	1 27.4	1 27.7	1 28.0	1 28.4
23	0 58.4	0 58.7	0 58.9	0 59.1	53	1 29.4	1 29.7	1 30.1	1 30.4
24	0 58.9	0 59.1	0 59.3	0 59.5	54	1 31.5	1 31.9	1 32.2	1 32.6
25	0 59.4	0 59.6	0 59.8	1 00.0	55	1 33.8	1 34.2	1 34.5	1 34.9
26	0 59.9	1 00.1	1 00.3	1 00.5	56	1 36.2	1 36.6	1 36.9	1 37.3
27	1 00.4	1 00.6	1 00.8	1 01.1	57	1 38.8	1 39.2	1 39.5	1 39.9
28	1 00.9	1 01.2	1 01.4	1 01.6	58	1 41.5	1 41.9	1 42.3	1 42.7
29	1 01.5	1 01.7	1 02.0	1 02.2	59	1 44.5	1 44.9	1 45.2	1 45.6
30	1 02.1	1 02.4	1 02.6	1 02.8	60	1 47.6	1 48.0	1 48.4	1 48.8
31	1 02.8	1 03.0	1 03.2	1 03.5	61	1 51.0	1 51.4	1 51.8	1 52.2
32	1 03.4	1 03.7	1 03.9	1 04.1	62	1 54.6	1 55.0	1 55.3	1 55.9
33	1 04.2	1 04.4	1 04.6	1 04.9	63	1 58.5	1 59.0	1 59.4	1 59.8
34	1 04.9	1 05.1	1 05.4	1 05.6	64	2 02.7	2 03.2	2 03.7	2 04.1
35	1 05.7	1 05.9	1 06.2	1 06.4	65	2 07.3	2 07.8	2 08.3	2 08.7
36	1 06.5	1 06.7	1 07.0	1 07.2	66	2 12.3	2 12.8	2 13.3	2 13.8
37	1 07.4	1 07.6	1 07.9	1 08.1	67	2 17.7	2 18.2	2 18.7	2 19.3
38	1 08.3	1 08.5	1 08.8	1 09.0	68	2 23.7	2 24.2	2 24.7	2 25.3
39	1 09.2	1 09.5	1 09.7	1 10.0	69	2 30.2	2 30.7	2 31.2	2 31.8
40	1 10.2	1 10.5	1 10.8	1 11.0	70	2 37.3	2 37.9	2 38.5	2 39.1

To obtain the Bearing at any other declination compute:

$$\text{Bear. Polaris (in minutes)} = \frac{\text{Polar Dist. (in minutes)}}{\cos \text{Lat.}}$$

Table 11-3

CORRECTIONS TO TIMES OF ELONGATION  
FOR DIFFERENT LATITUDES, 1964

Latitude	10°	15°	20°	25°	30°	35°	40°	45°	50°
West Elongation	+1.4	+1.1	+0.7	+0.3	+0.0	-0.3	-0.6	-0.9	-1.2
East Elongation	-1.4	-1.1	-0.7	-0.3	-0.0	+0.3	+0.6	+0.9	+1.2

Table 11-4. Bearing of Polaris at Elongation

Polar Distance	0° 54.20'	0° 54.29'	0° 54.40'
Latitude	Bearing at Elongation		
34°	1° 05.4'*		1° 05.6'*
34.65°	1° 05.92'	1° 06.01'	1° 06.12'
35°	1° 06.2'*		1° 06.4'*

\* Taken from Table 11-2.

c. Time of elongation of precise longitude.  
(Paragraph E. 1. c)

(1) Determine by interpolation the GCT  
of Eastern elongation for September 5, 1964 (Table 11-5).

$$\begin{array}{rcl} \text{August 28, 1964 GCT} & & 21^{\text{h}} 38.10^{\text{m}} \\ \text{Variation per day} = 3.91^{\text{m}} & & \\ \text{August 28 to September 5} = 8 \text{ days} & & \\ 8 \times 3.91^{\text{m}} = 31.28^{\text{m}} & & \underline{-31.28^{\text{m}}} \\ & & 21^{\text{h}} 6.82^{\text{m}} \end{array}$$

(2) Correct GCT to Local Standard Time  
(LST)

Correct GCT by applying correction  
found in Table 11-3. (Observation Latitude =  $34^{\circ}39'07''$  or  $35^{\circ}$  north).

$$\text{GCT for } 34^{\circ}39'07'' = 21^{\text{h}} 6.82^{\text{m}} - 0.5^{\text{m}} = 21^{\text{h}} 5.36^{\text{m}}$$

(3) Correct GCT to precise LCT by sub-  
tracting  $0.011^{\text{m}}$  for each degree longitude west of Greenwich (Observation  
longitude =  $86^{\circ}40'42''$  or  $86^{\circ}$  west).

$$\begin{array}{l} \text{Correction} = 87 \times 0.011^{\text{m}} = 0.96^{\text{m}} \\ \text{Precise LCT} = 21^{\text{h}} 5.36^{\text{m}} - 0.96^{\text{m}} = \\ 21^{\text{h}} 4.40^{\text{m}} \end{array}$$

#### NOTE

This correction is for the difference  
between a mean solar day and a side-  
real day.

(4) Correct LCT to Standard Time (CST),  
subtract  $4^{\text{m}}$  for each degree that the local meridian is east of the  
Standard Time Meridian ( $90^{\circ}$  meridian CST).

$90^\circ - 86^\circ 40' 42'' = 3^\circ 19.3' = 3.32^\circ$   
 Correction =  $3.32 \times 14^m = 13.28^m$   
 $\text{CST} = 21^h 5.36^m - 13.28^m = 20^h 52.08^m$   
 (Time of elongation at longitude  $86^\circ 40' 42'' = 20^h 52.1^m$   
 Convert to 12 hour clock  $20^h 52.1^m - 12^h = 8^h 52^m 6^s$  p.m. CST

2. Calculation for Observation of Polaris at Any Time  
 (from dusk to dawn)

a. Determine the bearing of Polaris off True North as follows:

(1) Use formula:  $Z = \frac{\sin t}{\cos h} P$

$Z$  = Bearing of Polaris  
 $t$  = Meridian angle (Local Hour Angle)  
 $h$  = True altitude  
 $P$  = Polar distance expressed in minutes of angle.

(2) Find  $t$  for first reading of observation at 7:00 p.m. CST September 5, 1964.

(a) Convert to 24 hour clock by adding 12 hours:  $7:00 + 12:00 = 19:00^h$

(b) Correct CST ( $90^\circ$  meridian for GCT by adding  $4^m$  for each degree west of Greenwich.

Correction =  $4^m \times 90 = 360^m$  or  $6:00^h$   
 $\text{GCT} = 19:00^h + 6:00^h = 25:00^h$

(c) Correct for one day.

$25:00 - 24:00 = 1:00^h$  GCT next day, September 6, 1964.

(d) Determine  $0^h$  GHA of Polaris from Table 11-6.

$0^h$  GHA of Polaris =  $315^\circ 10.4'$

Table 11-5

POLLARS FOR THE MERIDIAN OF GREENWICH

LATITUDE 41° N, 1964

Universal Time or Greenwich Civil Time

Date	Direct Observation	Previous Night Observation	Next Night Observation	Next Lower Observation	For Day
1964					
Jan.	10 2.0	11 2.0	12 2.0	13 2.0	14 2.0
Feb.	11 2.0	12 2.0	13 2.0	14 2.0	15 2.0
Mar.	12 2.0	13 2.0	14 2.0	15 2.0	16 2.0
Apr.	13 2.0	14 2.0	15 2.0	16 2.0	17 2.0
May	14 2.0	15 2.0	16 2.0	17 2.0	18 2.0
June	15 2.0	16 2.0	17 2.0	18 2.0	19 2.0
July	16 2.0	17 2.0	18 2.0	19 2.0	20 2.0
Aug.	17 2.0	18 2.0	19 2.0	20 2.0	21 2.0
Sept.	18 2.0	19 2.0	20 2.0	21 2.0	22 2.0
Oct.	19 2.0	20 2.0	21 2.0	22 2.0	23 2.0
Nov.	20 2.0	21 2.0	22 2.0	23 2.0	24 2.0
Dec.	21 2.0	22 2.0	23 2.0	24 2.0	25 2.0
1965					
Jan.	22 2.0	23 2.0	24 2.0	25 2.0	26 2.0

From Jan. 1 to Oct. 17 the time difference is by the 1964 day.  
From Oct. 18 to Dec. 31 the time difference is by the 1965 day.  
From Jan. 1 to Apr. 15 and from Oct. 26 to Jan. 1 the lower observation is for the next day.

Table 11-6

SOLAR EPHEMERIS SEPTEMBER 1964

For 0° Universal Time or Greenwich Civil Time

Day of Month	The Sun's Apparent Declination for 1 hour of Time	Diff. in Time 15 min - LCT + for 1 hour of Time	Diff. in Time 15 min - LCT + for 1 hour of Time	Diff. in Time 15 min - LCT + for 1 hour of Time	Diff. in Time 15 min - LCT + for 1 hour of Time
01	10 21.4	0.91	0.04	0.79	210 10.0
02	10 20.6	0.92	0.04	0.80	211 14.6
03	10 19.8	0.92	0.04	0.81	212 13.7
04	10 19.0	0.92	0.04	0.83	213 12.4
05	10 18.2	0.93	0.04	0.83	214 11.8
06	10 17.4	0.93	0.04	0.83	215 10.4
07	10 16.6	0.93	0.04	0.84	216 09.3
08	10 15.8	0.94	0.04	0.84	217 08.2
09	10 15.0	0.94	0.04	0.84	218 07.1
10	10 14.2	0.94	0.04	0.84	219 06.0
11	10 13.4	0.94	0.04	0.87	220 04.9
12	10 12.6	0.94	0.04	0.88	221 03.7
13	10 11.8	0.94	0.04	0.88	222 02.6
14	10 11.0	0.94	0.04	0.88	223 01.4
15	10 10.2	0.94	0.04	0.88	224 00.3
16	10 9.4	0.94	0.04	0.89	225 00.2
17	10 8.6	0.94	0.04	0.89	226 00.1
18	10 7.8	0.94	0.04	0.89	227 00.0
19	10 7.0	0.94	0.04	0.89	228 00.0
20	10 6.2	0.94	0.04	0.89	229 00.0
21	10 5.4	0.94	0.04	0.89	230 00.0
22	10 4.6	0.94	0.04	0.89	231 00.0
23	10 3.8	0.94	0.04	0.89	232 00.0
24	10 3.0	0.94	0.04	0.89	233 00.0
25	10 2.2	0.94	0.04	0.89	234 00.0
26	10 1.4	0.94	0.04	0.89	235 00.0
27	10 0.6	0.94	0.04	0.89	236 00.0
28	10 0.0	0.94	0.04	0.89	237 00.0
29	10 0.0	0.94	0.04	0.89	238 00.0
30	10 0.0	0.94	0.04	0.89	239 00.0
31	10 0.0	0.94	0.04	0.89	240 00.0

Table 11-7.

(e) Correct for GHA 1:00<sup>h</sup> from

$$\begin{aligned}\text{Correction} &= 15^\circ 2.5' \\ \text{GHA for 1:00 GCT} &= 315^\circ 10.4 \\ + 15^\circ 2.5 &= 330^\circ 12.9'\end{aligned}$$

(f) Correct for LHA by subtracting  
the precise longitude from GHA.

$$\begin{aligned}t &= 330^\circ 12.9' - 86^\circ 40.7' = \\ &\quad 243^\circ 32.2' \text{ or} \\ t &= 360^\circ - 243^\circ 32.2' = 116^\circ 27.8' \\ &\quad (\text{Use smaller value for } t)\end{aligned}$$

(3) Find h

(a) Interpolate from the Table 11-8  
for  $t = 116^\circ 27.8'$ . Add, or subtract, the correction as indicated in the  
table to determine the correct altitude.

$$\begin{aligned}t &= 116^\circ 27.8' \\ \text{Altitude} &= 34^\circ 39.1' \\ \text{Correction} &= 24.4'\end{aligned}$$

Correct Altitude  $34^\circ 14.7'$

$$h = 34^\circ 14.7'$$

(4) Find the value of P, using interpolation,  
from Table 11-1. The Polar distance for September 5, 1964, is  $54.28'$ .

(5) Calculate Z

$$(a) \quad \text{Bearing } Z = \frac{\sin 116^\circ 27.8'}{\cos 34^\circ 14.7'} \times 54.28'$$

$$Z = \frac{0.89522}{0.82664} \times 54.28'$$

$$Z = 58.73'$$

[illegible]138

**Table 11-7 (Continued)**

[illegible]

Date.	Mean of Greenish Crab Time				Sec.
	1st	115	125	1st	
1	130	130	130	130	130
2	130	130	130	130	130
3	130	130	130	130	130
4	130	130	130	130	130
5	130	130	130	130	130
6	130	130	130	130	130
7	130	130	130	130	130
8	130	130	130	130	130
9	130	130	130	130	130
10	130	130	130	130	130
11	130	130	130	130	130
12	130	130	130	130	130
13	130	130	130	130	130
14	130	130	130	130	130
15	130	130	130	130	130
16	130	130	130	130	130
17	130	130	130	130	130
18	130	130	130	130	130
19	130	130	130	130	130
20	130	130	130	130	130
21	130	130	130	130	130
22	130	130	130	130	130
23	130	130	130	130	130
24	130	130	130	130	130
25	130	130	130	130	130
26	130	130	130	130	130
27	130	130	130	130	130
28	130	130	130	130	130
29	130	130	130	130	130
30	130	130	130	130	130
31	130	130	130	130	130
32	130	130	130	130	130
33	130	130	130	130	130
34	130	130	130	130	130
35	130	130	130	130	130
36	130	130	130	130	130
37	130	130	130	130	130
38	130	130	130	130	130
39	130	130	130	130	130
40	130	130	130	130	130
41	130	130	130	130	130
42	130	130	130	130	130
43	130	130	130	130	130
44	130	130	130	130	130
45	130	130	130	130	130
46	130	130	130	130	130
47	130	130	130	130	130
48	130	130	130	130	130
49	130	130	130	130	130
50	130	130	130	130	130
51	130	130	130	130	130
52	130	130	130	130	130
53	130	130	130	130	130
54	130	130	130	130	130
55	130	130	130	130	130
56	130	130	130	130	130
57	130	130	130	130	130
58	130	130	130	130	130
59	130	130	130	130	130
60	130	130	130	130	130
61	130	130	130	130	130
62	130	130	130	130	130
63	130	130	130	130	130
64	130	130	130	130	130
65	130	130	130	130	130
66	130	130	130	130	130
67	130	130	130	130	130
68	130	130	130	130	130
69	130	130	130	130	130
70	130	130	130	130	130
71	130	130	130	130	130
72	130	130	130	130	130
73	130	130	130	130	130
74	130	130	130	130	130
75	130	130	130	130	130
76	130	130	130	130	130
77	130	130	130	130	130
78	130	130	130	130	130
79	130	130	130	130	130
80	130	130	130	130	130
81	130	130	130	130	130
82	130	130	130	130	130
83	130	130	130	130	130
84	130	130	130	130	130
85	130	130	130	130	130
86	130	130	130	130	130
87	130	130	130	130	130
88	130	130	130	130	130
89	130	130	130	130	130
90	130	130	130	130	130
91	130	130	130	130	130
92	130	130	130	130	130
93	130	130	130	130	130
94	130	130	130	130	130
95	130	130	130	130	130
96	130	130	130	130	130
97	130	130	130	130	130
98	130	130	130	130	130
99	130	130	130	130	130
100	130	130	130	130	130

**Table 11-7. (Concluded)**

(b) Convert hundredths of minutes to seconds:  $0^{\circ}58'46.8''$  (Bearing of Polaris at 7:00 P.M. CST September 5, 1964).

b. Repeat above process for all times the readings are to be taken. A minimum of 20 readings, 15 minutes apart should be calculated for a particular date of observation. When establishing a reference line that requires a very high degree of accuracy, observation should be made on at least two separate dates.

c. Plot a graph showing the path of Polaris. This will assist in finding errors in calculations. Refer to Figure 11-7. Prepare data sheet as shown in Figure 11-8. Fill in first three columns in preparation for actual observation.

## G. Taking Observations

### 1. Observations of Polaris at Elongation

a. Select a location for the instrument so that the line of sight will not be affected by adverse conditions such as heat from buildings, or strong, local wind currents.

b. Mount Wild T-3 Theodolite on Bruning Instrument Stand.

c. Establish a reference line. Correct magnetic north to true north or the first bearing of Polaris can be used as a reference. Points on reference line should be at least 100 feet apart.

d. "Buck-in" the theodolite on reference line, and set vertical and horizontal scales to "0" (zero).

e. Set vertical scale on desired altitude (local latitude).

### NOTE

Polaris should be in the instrument field of view.

f. Begin tracking Polaris 20 minutes before time of elongation (Paragraph F.2.c.). Readings may be taken approximately 10 minutes before and after exact time of elongation. Time known to be accurate within one minute is adequate.

LONGITUDE 86°40'42"  
 LATITUDE 34°39'07"

DATE Sept. 5, 1964

READING NO.	TIME	CALCULATED BEARING			ACTUAL READING FROM REF. LINE			DIFFERENCE BETWEEN CALCULATED & ACTUAL	
		Deg.	Min.	Sec.	Deg.	Min.	Sec.	Min.	Sec.
1.	7:00	0	58	46.8	0	59	36.8	+	50.0
2.	7:15	1	0	36.9	1	01	34.2	+	58.3
3.	7:30	1	02	11.1	1	02	58.0	+	46.9
4.**	4:45	1	03	29.8	1	04	39.9	+01	10.1
Check Reference Line									
5.	8:00	1	04	32.1	1	05	09.1	+	37.0
6.	8:15	1	05	17.7	1	05	47.5	+	29.8
7.	8:30	1	05	46.6	1	06	12.7	+	26.1
8.	8:45	1	05	58.5	1	06	17.2	+	18.7
***	8:52	1	06	0.6					
9.	9:00	1	05	53.6	1	06	03.6	+	10.0
Check Reference Line									
10.	9:15	1	05	31.4	1	05	40.7	+	9.3
11.	9:30	1	04	52.3	1	04	59.8	+	7.5
12.	9:45	1	03	56.5	1	03	52.0	-	4.5
13.	10:00	1	02	43.8	1	02	33.1	-	10.7
14.	10:15	1	01	14.7	1	01	04.3	-	10.4
Check Reference Line									
15.	10:30	0	59	29.9	0	59	14.3	-	15.6
16.	10:45	0	57	29.4	0	57	06.2	-	23.2
17.	11:00	0	55	15.0	0	54	52.5	-	22.5
18.	11:15	0	22	43.5	0	52	25.5	-	18.0
19.	11:30	0	49	59.4	0	49	32.6	-	26.8
20.	11:45	0	47	02.1	0	46	37.3	-	24.8

Check Reference Line

\* See Figure 11-7 for a plot of the data

\*\* Check calculation - do not use value in average

\*\*\* Point calculated by observation of Polaris at Elongation

Figure 11-8. True North Line Data Sheet\*

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g. Adjust azimuth until Polaris is traveling in a vertical line along the vertical reticle of the instrument. The first reading should not be taken until the true vertical travel has been observed for approximately 2 minutes.

h. Read azimuth scale of instrument, and record setting.

i. "Dump" scope, and set vertical reticle on Polaris. Read azimuth scale of instrument and record setting.

j. Repeat step G. 1. i as many times as reasonably possible within the 20 minute period of time.

k. Check instrument on reference line.

l. Average the readings.

#### NOTE

The average will be the bearing of Polaris at elongation from the reference line.

m. Set instrument on the observed bearing (par. G. 1. l) of Polaris at elongation.

n. Set azimuth scale to 0.

o. Turn-off the calculated bearing (par. F. 2. a or F. 2. b.) on the azimuth scale of the instrument

#### NOTE

The instrument will be on the True North Line.

p. Establish new reference points on this line of sight which is a True North Line.

2. Observation of Polaris At Any Time

- through G. 1. c.
- a. Perform steps as outlined in paragraph G. 1. a
  - b. Position radio and clock near the instrument.
  - c. "Buck-in" theodolite on reference line, and set azimuth scale to 0.
  - d. Set the theodolite so the vertical scale is on the proper altitude and the azimuth scale is on the first calculated bearing. (This should bring Polaris into view 10 minutes before the readings are to begin.)
  - e. Tune radio to station WWV for time signal. The time signal from WWV can be used as the MARK, or exact time for the reading.
  - f. Synchronize clock with time signal.
  - g. Begin tracking Polaris 5 minutes before the first observation.
  - h. Have timekeeper and recorder observe the time, and keep instrument operator informed of the countdown. The last 10 seconds should be counted off.
  - i. Read and record the bearing. See Figure 11-8 for recording data.
  - j. "Dump" the instrument (do not reset the azimuth scale), and continue to track Polaris and repeat steps G. 2. g and G. 2. i.
  - k. Repeat steps G. 2. g through G. 2. j throughout the observations except between the 4th and 5th, 9th and 10th, 14th and 15th, and after the 20th reading. Check the reference line to verify the instrument is still properly set.

NOTE

If the instrument is off the reference line, disregard the readings taken since the previous verification of the instrument and reset the azimuth scale to zero on the reference line, before readings are resumed.

## H. Reduction of Data

1. Determine the difference between the calculated value and the actual reading referenced from the reference line.  
(See last column of Figure 11-8).

2. Determine a statistical average of the differences.  
The statistical average value will be the correction to be applied to the reference line.